

PROPERTIES OF QSO METAL LINE ABSORPTION SYSTEMS AT HIGH REDSHIFTS: NATURE AND EVOLUTION OF THE ABSORBERS AND NEW EVIDENCE ON ESCAPE OF IONIZING RADIATION FROM GALAXIES*

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ABSTRACT

Using Voigt-profile-fitting procedures on Keck HIRES spectra of nine QSOs we identify 1099 C IV absorber components clumped in 201 systems outside the Lyman forest over $1.6 \lesssim z \lesssim 4.4$. With associated Si IV, C II, Si II and N V where available we investigate bulk statistical and ionization properties of the components and systems and find no significant change in redshift for C IV and Si IV while C II, Si II and N V change substantially. The C IV components exhibit strong clustering but no clustering is detected for systems on scales from 150 km s^{-1} out to 50000 km s^{-1} . We conclude the clustering is due entirely to the peculiar velocities of gas present in the circumgalactic media of galaxies. Using specific combinations of ionic ratios we compare our observations with model ionization predictions for absorbers exposed to the metagalactic ionizing radiation background augmented by *proximity* radiation from their associated galaxies and find the generally accepted means of radiative escape by transparent channels from the internal star-forming sites is spectrally not viable for our stronger absorbers. We develop an active scenario based on runaway stars with resulting changes in the efflux of radiation that naturally enable the needed spectral convergence and in turn provide empirical indicators of morphological evolution in the associated galaxies. Together with a coexisting population of relatively compact galaxies indicated by the weaker absorbers in our sample the collective escape of radiation is sufficient to maintain the IGM ionized over the full range $1.9 \lesssim z \lesssim 4.4$.

Subject headings: intergalactic medium — cosmology: observations — galaxies: formation — quasars: absorption lines — quasars: individual

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1. INTRODUCTION

The spectra of exceptional quality delivered by the Keck I High Resolution Spectrograph (HIRES; Vogt et al. 1994) have revealed individual metal absorption features related to the high-redshift Lyman forest for a large fraction of the stronger lines

(Cowie et al. 1995; Tytler et al. 1995; Songaila & Cowie 1996; Womble et al. 1996). By redshift $z \sim 3$ such absorbers are found to have a median carbon abundance approximately 10^{-2} of solar (with substantial scatter) and Si/C abundance similar to Galactic halo stars, although these values are based on rather uncertain ionization corrections (Songaila & Cowie 1996; Rauch et al. 1997).¹ There is evidence for some metal enrichment also at considerably lower H I column densities (Ellison et al. 2000; Schaye et al. 2000a, 2003). While it is not yet fully clear how the pollution of the general forest material has come about, the observed metal absorbers provide a powerful *in situ* probe of early stages in the growth of structure and the formation and evolution of galaxies and give an observational approach to determining the spectral character of the cosmological ionizing radiation background at those times.

Detailed hydrodynamical simulations of cosmological structure formation in the presence of a photoionizing background which yield direct quantities for comparison with observations have been developed by several groups (Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Davé & Tripp 2001; Viel et al. 2002) and much new work continues in this field. In these simulations it is straightforward to compute the neutral hydrogen absorption that would be produced in the light of a background QSO along an arbitrary line of sight through the simulation volume. It is impressive that such results can reproduce the evolving spectral appearance and statistical properties of cosmologically distributed H I absorbers in considerable detail, spanning the range from the weakest detected to those showing damped Lyman α profiles. An important insight gained from such simulations is that galaxies and H I absorbers develop naturally together in the hierarchical formation of structure. High column density lines ($N(\text{H I}) \gtrsim 10^{17} \text{ cm}^{-2}$) arise from radiatively cooled gas associated with forming galaxies in collapsed, high density, compact regions. Lower column density absorption ($N(\text{H I}) \lesssim 10^{15} \text{ cm}^{-2}$) occurs in the shallower dark matter potential wells, containing gas in various stages of gravitational infall and collapse; typically these are in the form of flat-

tened or filamentary structures of moderate overdensity with Doppler parameters that are often set by peculiar motions or Hubble flow in addition to thermal broadening. Gravitational, pressure and ram-pressure confinement all play significant roles. Such a scenario in which metal absorption arises in gas assumed to be homogeneously enriched is discussed by Rauch et al. (1997). In their simulation the large velocity widths of some metal absorbers arise from interactions between associated protogalactic clumps or from alignments of groups of such objects along chance filaments in the line of sight. This simple model does not include stellar “feedback” by galaxies which could strongly modify the local gas distribution and kinematic state by producing outflows both enriching the nearby medium and opposing the general infalling motion. Increasing attention has since been given to accounting for stellar processes in galaxy formation simulations (Theuns et al. 2002; Croft et al. 2002; Springel & Hernquist 2002; Marri & White 2003; Nagamine et al. 2004) and recent much enhanced sophistication in the treatment of star formation and feedback has enabled the study of associated metal absorbers in ever more realistic simulations (e.g., Kawata & Rauch 2007; Oppenheimer et al. 2009, 2012; Cen & Chisari 2011; Smith et al. 2011; Shen et al. 2012, 2013) alongside considerable observational evidence that has been reported (e.g., Rauch et al. 1999, 2001; Bond et al. 2001; Adelberger et al. 2003, 2005b; Aguirre et al. 2005; Simcoe et al. 2006; Steidel et al. 2010).

The strength and spectrum of the metagalactic ionizing radiation background at high redshift and the nature of the sources which ionized the intergalactic medium (IGM) have long been outstanding issues in cosmology. Although at relatively low to intermediate redshifts QSOs had been accepted as the main contributors to the metagalactic ionizing radiation, there was speculation on whether they dominate at the highest redshifts (Bechtold et al. 1987; Donahue & Shull 1987; Shapiro & Giroux 1987; Bajtlik, Duncan, & Ostriker 1988; Meiksin & Madau 1993; Haardt & Madau 1996). Most of later studies demonstrate that QSOs fall short of producing enough flux to satisfy measurements at redshifts significantly beyond $z \sim 3$ where the space density of bright QSOs is sharply decreasing (Cooke et al. 1997; Madau et al. 1999; Scott et al. 2000; Bianchi et al. 2001). The presence

¹Damped Lyman α (DLA) absorbers suffer much less from this limitation (e.g., Pettini et al. 2008).

of a strong population of high redshift Lyman-break galaxies (Steidel et al. 1996, 1999) and the apparent observations of significant flux beyond the H I Lyman limit escaping from such galaxies (Steidel et al. 2001; Shapley et al. 2006; Iwata et al. 2009) lend strong support to the idea that star-forming regions dominated the ionizing background at early times (Haehnelt et al. 2001; Bolton et al. 2006). The spectral shape of the ultraviolet background radiation should be reflected in the ionization pattern of QSO metal system absorbers (Chaffee et al. 1986; Bergeron & Stasińska 1986; Steidel & Sargent 1989; Vogel & Reimers 1993; Giroux & Shull 1997; Boksenberg et al. 2001; Bergeron et al. 2002; Agafonova et al. 2007) and this can be used to identify the character of the ionizing sources if the spectral modifications due to propagation of the radiation through the IGM are properly accounted for (Haardt & Madau 1996, 2012; Madau & Haardt 2009). In turn, this can contribute to determinations of heavy element abundances in denser regions of the IGM as well as in outer circumgalactic regions (CGM).

In this paper we study the statistical properties and ionization states of a large sample of metal absorbers and trace their evolution in redshift, greatly extending our earlier work (Boksenberg 1997; Boksenberg et al. 2001, 2003). In §2 we describe the observations and initial data reduction and in §3 outline our analysis of the absorbers and show that these exist consistently as multi-phase-ionization systems containing individually identifiable *single-phase component regions* of widely-ranging ionization state. In §4 we give full tables of results with supporting information, comments and displays and in §5 define samples which we use in the following sections. In §6 we derive statistical properties and the redshift evolution of absorber system and component quantities, also contrasting properties of absorbers physically close to the sightline QSOs. In §7 we present clustering studies from which we deduce the nature of the contributing absorbers. In §8 we present redshift distributions of ionic ratios and ionic ratio combinations. In investigative studies aiming to fit the latter observations we compare these with results of photoionization modeling using the CLOUDY code (Ferland et al. 1998, 2011) within which we apply exposure by the metagalactic ionizing radiation background from QSOs and galax-

ies at large (Haardt & Madau 2012), also considering possible effects of delayed reionization of intergalactic He II, collisional ionization and absorber parameters, but find all these insufficient to match our data for the strong absorbers in our sample particularly at the higher redshifts in our range. We then explore the addition of direct radiation at the absorbers emitted from their local galaxies and discover that to meet the ionic patterns we observe requires considerable modification of the spectral distribution of the escaping ionizing radiation from that commonly assumed. In §9 we draw strong new conclusions about the mechanism needed to bring this about and demonstrate empirically that an active process based on runaway stars can, in natural and robust fashion, enable quantitative matches to the observed ionic ratio combinations for the strong absorbers. Then, together with similarly derived indications for a co-existing population of galaxies associated with the numerous weaker absorbers in our sample we are able to conclude with a specific evolving picture of galaxy geometrical properties that can yield levels of escape fraction adequate for necessary contributions to the assumed metagalactic ionizing radiation background at least over $1.9 < z < 4.4$. We summarize our results in §10.

This paper follows from Boksenberg et al. (2003), using the same data base with some adjustment to sample membership and addition of a few measured values obtained from the original spectra. However the analytical content and conclusions are brought up to date and greatly extended and benefit from the remarkable intervening developments in the associated fields.

Unless otherwise stated, at appropriate sections below we assume a $(\Omega_M, \Omega_\Lambda, \Omega_b, h) = (0.3, 0.7, 0.045, 0.7)$ cosmology.

2. OBSERVATIONS AND DATA REDUCTION

The work presented in this paper is based on HIRES observations of a set of nine QSOs with redshifts $2.32 < z_{\text{em}} < 4.56$, listed with associated information in Table 1. Most of the spectra are obtained using a slitwidth of $0''.86$ yielding a resolution $\sim 6.6 \text{ km s}^{-1}$ FWHM covered by roughly three pixels. The exception is for the gravitationally-lensed object Q1422+2309 (Pat-

naik et al. 1992) of which, to confine our observations to a single sightline consistent with the rest, we take the data from image component C obtained in excellent seeing ($\lesssim 0''.6$) using a narrower slitwidth, $0''.574$, yielding $\sim 4.4 \text{ km s}^{-1}$ FWHM, and with position angle set to minimize contamination from the closely-spaced neighbouring components A and B (Rauch et al. 1999, 2001).

Two partially overlapping configurations for each wavelength region gives complete coverage of the free spectral range for the HIRES echelle format. The data are reduced as described in Barlow & Sargent (1997), with the individual exposures for each QSO wavelength-shifted to heliocentric, vacuum values and added together with weight according to the signal-to-noise ratio (S/N). Continuum levels are delineated by means of polynomial fits to regions apparently free of absorption features and these are used to produce continuum-normalized spectra ready for the analysis of the absorption systems.

The spectra show complex and quite large changes in S/N along their length due to the variations in instrument efficiency, the sharply uneven signal over the range resulting from the overlapped setups, the intrinsic spectral variation of signal intensity from the QSOs themselves, and the incidence of atmospheric emission and absorption features. In order to account for these individual patterns of S/N in the subsequent analysis procedure (see §3.2), matching statistical 1σ error arrays are built up during the reduction stages for use in association with each completed spectrum file. A general indication of minimum signal quality is given in Table 1 by S/N values sampled at a few rest-wavelength positions common to each spectrum and avoiding the QSO broad emission lines (within which the S/N is higher).

The primary regions of the nine spectra that are used for obtaining the data in this paper are displayed in Figure 1. Atmospheric emission and absorption features become progressively more dense with increasing redshift. For clarity we have removed these from the displays and bridge the gaps with *thin continuous lines*. The positions of the atmospheric emission features are identified by vertical ticks with lengths crudely graded to indicate intensity, and the complex pattern of absorption is shown by indicative full spectra set below the QSO spectra; both reflect the accumulated individual

heliocentric shifts applied discretely over the observing runs to correct the QSO spectra. More on this and much additional information is given in footnotes to Tables 2–10 (see §4.1).

3. DETERMINATION OF ABSORPTION-LINE PARAMETERS

3.1. Selection Strategy

Outside the Lyman forest the metal absorbers typically appear as well-defined clumps with velocity structure ranging up to a few hundred km s^{-1} in width. In general there are wide expanses of apparently clear redshift space between such clumps. We classify these absorbing entities as *systems* and identify them by the presence of C IV, the prevalent ion and the only one detected in the weakest systems. Stronger systems also contain lines of some, or occasionally most, of the species Si IV, C II, Si II, N V, O I, Al II, Al III, Fe II and Ni II, if available in the observed spectral range. Within each system we define a population of physical “clouds”, termed *components*, each having a Gaussian velocity distribution of specific width and which collectively reproduce the system velocity structure in detail.

Because of blending with H I absorption for metal lines in the Lyman forest, which becomes increasingly severe to higher redshifts, our data sample is built primarily on measurements made outside the forest; only in some exceptionally favourable cases are metal lines in the forest included.

For the work presented in this paper we concentrate on the lines C IV $\lambda\lambda 1548.2049, 1550.7785$, Si IV $\lambda\lambda 1393.7602, 1402.7730$, C II $\lambda 1334.5323$, Si II $\lambda 1260.4221$ and N V $\lambda\lambda 1238.821, 1242.804$ (vacuum wavelengths).² If a line is not detected at the wavelength expected from the presence of other species in a given component of the same system, an upper limit is determined (see §3.2). In systems with Si II $\lambda 1260.4221$ obscured in the forest we substitute $\lambda 1526.7070$ and include $\lambda 1304.3702$ if available, but these are relatively much weaker and detected only when Si II is strong; when not detected, the upper limits obtained from these are often too high to be useful.

²All rest-frame wavelengths and related atomic data used here are from Morton (2003).

3.2. Profile-Fitting Analysis

For the analysis of our spectra we use the Voigt profile-fitting code VPFIT developed by Carswell and collaborators (Carswell et al. 2002) and kindly made available to us. VPFIT is a χ^2 -minimization program capable of making detailed fits to the absorption profiles of several different transitions simultaneously. It estimates redshift, z , Doppler parameter, b ($= \sqrt{2}\sigma$) which includes thermal and Gaussian turbulence broadening terms, and column density, N , all with their associated errors, for the individual components of the systems in the defined fitting regions. For the instrumental resolution included in this procedure we take $b_{instr} = 2.83 \text{ km s}^{-1}$ for Q1422+239C and $b_{instr} = 3.96 \text{ km s}^{-1}$ (6.61 km s^{-1} FWHM) for the rest (see §2). Since the χ^2 -minimization technique operates on the reduced spectra there is a degree of correlation between neighbouring pixels arising from the rebinning of the data in the reduction process. To compensate for this slight smoothing we derive an error-correction file for each spectrum obtained by comparison of values at many wavelengths in the accumulated error array with directly measured values of the root-mean-square fluctuation in the final continuum. The error-correction factor is relatively small, typically in the range 1.1–1.3, and is applied from this file automatically within VPFIT.

While the lower ionization species often are dominated by narrower components and the higher by broader, we find, consistent with the S/N, that *regardless of width* a matching range of components *having representation across the ionized species* invariably are present, albeit with different strengths. We conclude that the different components observed in any system trace individual physical cloud regions, and, depending on the specific ionization states of these regions, the associated species contribute appropriately to the individual balance of component absorption strengths. In other words, the individual components identified in the metal systems quite closely represent *single-phase-ionization absorbing regions co-existing in multi-phase system complexes*. We demonstrate this here with a simple example case. Following the analysis procedure we describe in detail in this section, and using a system at $z = 2.285$ in Q1626+6433, we show selectively in Figure 2 (taken from Figure 4 and

Table 2) how the derived components are distributed in radial velocity among the low to high ionic species. While different components dominate in Si IV, C II, Si II and N V, all coexist as blended, strong constituents of the C IV overall profile, well-separable in our Voigt profile-fitting analysis. Note in particular the two nearly coincident (in redshift) components 2 and 3 having markedly different widths: both are strong in C IV but change greatly in dominance between the observed low and high ionization counterpart species. Among these Si IV shows related intermediate behaviour. Being closely at the same redshift, simplistically these two identifiable regions could be separated along the line of sight or separated radially within a single structure. Either way, the physical components of this simple absorption system straightforwardly represent individual regions having quite different degrees of ionization unambiguously traceable through the species. Along the same lines, a considerably more complex example is discussed in §4. We deal with component ionization structure more quantitatively in §8 and §9.

The unifying assumptions we therefore adopt in our analysis are (i) that the component redshift structure seen in one ion corresponds exactly to that in any other ion of the same system, while allowing that in general the relative strengths of the corresponding components be different, and (ii) that the b -values of corresponding components in different ionic species of a given system each include the same temperature and same Gaussian turbulent motion associated by the expression (Rauch et al. 1996)

$$b_{ion}^2 = b_{turb}^2 + \frac{2kT}{m_{ion}}, \quad (1)$$

where m_{ion} denotes the atomic mass of the ion. This relation is formally handled within the VPFIT procedures.

For each QSO the first step in our procedure is to identify all C IV absorption doublets evident outside the forest. In VPFIT, doublet or other members of the same ion automatically are fitted with the same parameters when the wavelength regions where they occur are specified. We begin our analysis by deriving initial redshifts of all necessary components that can be identified in the fitting of the profiles of the C IV doublets

alone. Next, in a given system, all other members of our defined set of ionic species potentially present in the available wavelength range, *whether apparent or not*, are assigned the same initial set of component redshifts and linked to track together with C IV in the subsequent fitting stages. Doublet species are accepted even when only one well-defined member is outside the Lyman forest. The component b -values for all ionic species of the same atom (C IV with C II and Si IV with Si II) are also linked to track together. Finally, to enable VPFIT to derive mutually consistent b -values among the different species, following the requirements discussed above, we assign initial trial component temperatures and within VPFIT physically link the b -values of all atomic species present. To set these initial temperatures we use, as an indicative aid, results given by Rauch et al. (1996) from a formal decomposition into thermal and Gaussian non-thermal motions in a sample of related C IV and Si IV absorption components, shown in their Figure 3 as a plot of C IV thermal against total b -values. Finally, VPFIT then is allowed to attempt simultaneous integral fits to the distributed common components making up the line profiles of the different species in a system by iteratively adjusting in physically consistent fashion the components’ common temperatures and individual total b -values and column densities, while refining the common redshifts, in a first complete pass. Potential components not detected “drop out” of the analysis and subsequently are assigned upper limits in the manner described below. Equally, if a member of the set of associated species in a system has components which are mildly saturated but others have clear profiles, the procedure enables the saturated components to be identified in the analysis with parameters in common and be assigned consistent column densities with appropriate errors.

In this consolidated procedure involving all species in a system, most members are well separated from lines at other redshifts and matters are generally straightforward. When blending with any species at other redshifts does occur we find reliable values usually can be obtained by simultaneously fitting all members of the different systems present. In similar fashion, where necessary we accommodate all but the most severe interference from atmospheric emission and absorption

within our profile fitting analysis. In the relatively few cases where some or all components of one doublet member are too badly contaminated, we make do solely with the equivalent components of the other member. Equally, if both members are partially contaminated we select the available component structure from free areas between the two. Component parameter values judged to be too uncertain due to blending or contamination are excluded from the subsequent scientific analysis.

Rauch et al. (1996) derive a mean temperature 3.8×10^4 K for their sample but note that their analysis is dominated by narrower components which have smaller measurement errors than the more uncertain broader features. They also suggest that a tail in the b -value distribution towards large values, apparently indicating temperatures beyond 10^5 K, may well represent blends of components. Our analysis supports this view. Since C IV is more common and generally stronger than the other species, we note that a blend of components representing a typical mix of relatively high ionization regions tends often to appear significantly broader in C IV than Si IV due to the relative weakness of Si IV. If interpreted as a *single* feature such a blend indeed is likely to indicate an erroneously high temperature. Furthermore, we show in §8.4 that collisional ionization at temperatures near 10^5 K cannot be a significant contender for the absorbing regions we observe.

For the relatively few *broader* components present we find our fits to the observed profiles are generally consistent with a dominant turbulence contribution, there being relatively little difference in the b -values among the species, although with considerable uncertainty in the balance between the thermal and turbulence contributions in some shallow cases. In our analysis we set the temperature of all these broader components at the nominal mean value 3.8×10^4 K given by Rauch et al. (1996).³ Nevertheless, we show now in the following that there is little dependence on temperature in our results involving the observed broader lines.

To explore the sensitivity of this approxima-

³Although uncertain as we have already commented, such a value may well be consistent for relatively low density regions, as we indicate in §8.5.

tion we use a complex system at $z = 2.291$ in Q1626+6433 described in §4.2 and shown in detail in Figures 4 and 6. This is an unusual system containing several broad components which overlap numerous narrow ones. It is an appropriate example because in the fitting process components are not treated in isolation but adjusted relative to one another to achieve the overall fit to the data; the degree to which a given component is influenced by others in this process then depends on their relative strengths over its range of overlap. We compare the column density results for all components in the complex system from two separate computational runs using the widely-spaced fixed temperatures 1×10^4 K and 1×10^5 K collectively assigned to the three broadest components, 2, 4 and 14 identified in Figure 6 (where we use the nominal temperature 3.8×10^4 K). These two temperatures exceed the bounds expected for clouds of low metallicity and density photoionized by the intergalactic ultraviolet background radiation (see §8.5), and make a stringent test (note however, as already indicated above, in using this artificial range we do not imply that at the upper temperature the broad components are collisionally ionized). In the two cases the initial temperature assignments of the remainder of the components are made identical to those in the nominal case, following the procedure already described. In Figure 3 we show the resultant column densities for C IV, Si IV, C II and Si II obtained. The two sets of values are not significantly different, nor do they differ significantly from our results using the adopted nominal temperature for the three broadest components. It is apparent that the derived column densities for the individual components are very little affected by the adopted thermal properties of the *broad* components in an absorption complex and gives us confidence that our necessarily approximate approach for these nevertheless gives a sound procedure for obtaining reliable column densities for all the components. We give the broad absorption features further attention in §4.

The more constrained temperature bounds set by the widths of the *narrower* components in effect make the derived column densities for these, also, relatively insensitive to temperature. Such insensitivity to profile width applies equally for the instrumental profile, which varies by $\sim \pm 3.8\%$ in velocity width over the spectral range (Barlow

& Sargent 1997), and allows us to use a single, averaged, figure for each spectrum, as given earlier.

In some occasional instances a minor velocity shift relative to C IV, typically of a small fraction of 1 km s^{-1} , is made during the fitting process to improve the relative alignment of one or other of the profiles of widely separated species in the same system. Shift patterns are different among the QSOs and not all show detectable internal misalignments. The need for such slight shifts both between C IV and Si IV and, when available, between widely spread Si II transitions, indicates that these are not due to any physical ionization phenomena. As indicated by Barlow & Sargent (1997), we attribute the observed small misalignments to slight departures from true of the polynomial fits to the wavelength scale. Notwithstanding, as we establish from “before and after” cases, even without correction there is no significant effect on the derived column densities or b -values.

Component parameter errors as given by VPFIT are nominally 1σ values, but confusion between too-closely overlapping components with comparable parameters can give very large apparent errors due to uncertainty in value assignments between them.⁴ Consequently, in making our profile fits we avoid “overfitting” and adopt the general rule to end with the minimum number of components that give a reasonable fit after achieving a reduced χ^2 close to 1 per degree of freedom globally for the set of spectral regions linked in the analysis.

Generally our initial procedure results in a set of profiles which correspond well with the data for all of the components detected in each species. We iterate the process by making a further two or three VPFIT runs while minimizing the necessary number of components. For some strong, well-separated, components, reliable b -values sometimes can be obtained independently for Si as well as C, although such cases are relatively few.

At the conclusion of the fitting process for each system we obtain the associated errors on the component column densities alone by fixing the corresponding values of z and b -value in a final itera-

⁴Nevertheless, the combined column densities in such cases remains accurate and VPFIT then gives the correct error for the *total* column density of a set of adjacent components in a complex.

tion. In this operation we also derive upper limits for all potential components within the different species which have been too weak to survive the first pass of the analysis. We do this by re-introducing them with the appropriate fixed values for z and b -value and a small assigned column density well below the level of significance. The associated error values which are obtained become the adopted 1σ upper limits; all such values are on the linear portion of the curve of growth.

It is important to note that the wide range of ionization conditions generally found within a complex system means that determinations of ionic *ratios* cannot accurately be made from ratios of *total* system quantities: to be physically meaningful they must be determined individually from the components of the multi-phase systems, as we do later in this paper. Moreover, when significant system structure is identifiable in an absorption spectrum the intrinsic ability of the Voigt profile-fitting technique to segregate different absorbing regions in a complex system gives it significant advantage over the apparently more direct method of computing optical depths throughout a system (Savage & Sembach 1991; Songaila 1998) because the latter cannot account for overlapping blends of adjacent components, interlopers from other systems or differential temperature broadening between species of the same physical component.⁵

4. PRESENTATION OF RESULTS

4.1. The Data

Following the prescription outlined in the previous section, for each system we obtain excellent simultaneous fits over all species with a single pattern of component redshifts and appropriately linked b -values. As an illustration of the method, we show in Figure 4 a set of our detailed VPFIT results for Q1626+6433. We include all available target transitions superimposed on the observations for all detected systems having more than

just C IV accessible outside the Lyman forest. The spectra of all nine QSOs (refer to the condensed displays in Figure 1) are treated equally and in Tables 2–10 we list the full body of values derived, here with “unaccompanied” C IV features included. Column 1 gives the absorption redshift z as vacuum, heliocentric values; column 2 gives b -values for C; column 3 gives linked b -values for Si as described in §3.2, shown bracketed, and independent values when left as a free parameter, unbracketed; columns 4 to 8 give column densities; and column 9 identifies components by number within a system. For N, derived b -values are not listed but with its comparable atomic mass these intrinsically are close to those of C when representing the same component. Each system is sub-headed in the tables with the mean redshift of its constituent components. Where there is severe contamination, strong saturation or too much confusion from blending by lines at other redshifts to give useful quantities, no entry is given and explained in a footnote. The listed b -values for C almost always are the result of fits to C IV which usually dominates in strength over C II. In the rare cases when component regions have low ionization and C IV is very weak, independent b -values are derived solely from C II (and additionally Si II when left as a free parameter). In all, for the well-separated, stronger components the formal 1σ error in z typically is $\lesssim 0.000005$, and in b -value (for C, and Si when independently derived), $\lesssim 0.5 \text{ km s}^{-1}$.

Very few indeed of the absorption features in our spectra remain unidentified and of these most are very weak and some may be spurious. *No dense forest of weak metal lines* is seen even in the spectra having the highest S/N in our sample (see also: Ellison et al. 2000; Aracil et al. 2004). To allow ready comparison among the QSOs, in Figure 5 we show “spike diagrams” displaying the column densities of all *detected* components identified in Tables 2–10; note that the vertical scales for Si IV, Si II and N V are lower by 1 dex than for the others. Systems containing one or more components with significant Lyman α damping wings (we take the column density $N(\text{H I}) \gtrsim 10^{18.7}$) are marked *d*. The missing indeterminate values indicated in the tables are relatively few and the gaps have only a minor effect on the appearance of these diagrams. The coverage in redshift outside the Ly-

⁵However, for very weak or heavily contaminated signals related to low-density regions of intergalactic gas, not easily detectable directly, the optical depth technique coupled with multiple stacking of spectra introduced by Cowie & Songaila (1998) becomes a powerful tool in such circumstances (Ellison et al. 2000; Schaye et al. 2000a; Aguirre et al. 2002; Aracil et al. 2004).

man forest for the main transitions of our sample occurs between two dotted vertical lines shown in each frame except for Si II where we include such limits for all three transitions $\lambda\lambda\lambda 1260, 1304, 1527$. Present in the figures are the rare values reliably obtained in the Lyman forest for the standard lines of Si IV, C II, Si II and N V, clarified in the table footnotes.

4.2. Broad Absorption Features

As introduced in §3 a number of systems contain one or more broad components (up to a few $\times 10 \text{ km s}^{-1}$), generally of high ionization, self-consistently present in both members of the C IV doublet, that overlap in velocity space with many of the more numerous narrower components. Often a broad feature protrudes (in velocity) at the edge of a system boundary and can be seen directly as having a structureless appearance. In some cases the presence of a significant broad feature immersed among the body of narrow components in a system is required to reproduce the profile of one or more of the observed species. While we could contrive to construct the broad features from a solid blend of numerous narrow components we do not believe this is justified by the data, and good, consistent, fits using single broad components are obtained in general. Nevertheless, the implicit model envisaged in the VPFIT profile constructions characterizes each assumed cloud in a system simply by thermal and Gaussian turbulence broadening, while significant velocity *gradients* could also feature in the true overall absorption profile. Broad, high ionization components thus might represent regions of low volume density dominated by bulk motions (Rauch et al. 1996). Limitations to the detection of weak, broad components are discussed in §6.5.

A simple example with partially exposed high ionization broad components is the $z = 2.056$ system in Q1626+6433: the full observed range of species is displayed in Figure 4 and the constituent components of the C IV $\lambda 1548$ profile are shown in the upper left panel of Figure 6. In the latter, component 1, with $b \sim 21 \text{ km s}^{-1}$, is well enough separated from the others for its smooth outline to be clearly seen, and component 4, with $b \sim 55 \text{ km s}^{-1}$, although shallower (and partially overlapping with component 1) reveals a smooth extended wing. The associated two panels on the

upper right separately show combinations of the broad and narrow components.

In the lower panels of the same figure we show details of the $z = 2.291$ system in Q1626+6433, already used in §3.2, as a more complex as well as more comprehensive example, with broad features which are more immersed in the system. We go first to the panels on the left. The narrower components, $b(\text{C IV}) \lesssim 10 \text{ km s}^{-1}$ (see Table 2), here mostly have quite low ionization, with C II relatively strong; components 11 and 17 are the exceptions. Of the broader components, 2 and 4 unusually also have significant strength in C II, while the remainder have relatively high ionization with C IV strong and C II very weak or undetected.

The associated three sets of panels on the right highlight different subsets of these components. While the contributions of the combined high ionization components dominate the overall profile of C IV (middle set), it is particularly striking that the embedded combined subset of narrow, lower ionization components (top set) closely resembles the Si IV overall profile and indeed the C II profile. As stressed before, this emphasises the successful segregation of differently ionized regions. Of the broadest components (bottom set) the high ionization component 14, with $b \sim 32 \text{ km s}^{-1}$, is the strongest by far in C IV and the only significant component identified in the weak N V profiles shown in Figure 4. Fox et al. (2007a) discuss the origin of broad and narrow C IV components in DLA and sub-DLA systems.

5. DEFINITION OF SAMPLES

From the data in Tables 2–10 we define two samples *sa* and *sb*. Sample *sa* is selected, as far as possible, to be statistically homogeneous; we use this for the investigations of properties in §6. Sample *sb*, enlarged as defined below, is used in §8 and §9 to probe the ionization state of the gas through individual ionic *ratios* which does not, within defined limits, require a statistically homogeneous population of absorbers. For clustering studies in §7 we use both samples, as there indicated.

We find from VPFIT trials using selected higher redshift systems having several available Lyman series members, for which we assume the H I profiles contain at least the component populations identified in the metals, that the absorbers in our

chosen samples generally are optically thin in the Lyman continuum. However, higher members of the Lyman series are not uniformly available in the redshift range of our data. From Lyman α alone, the strongly saturated nature of most of the observed system profiles, as can be seen from the examples in Figure 4, compounded by the large thermal broadening experienced by H I relative to the metal species studied here, causes severe confusion among adjacent H I components in a great many of the systems. Consequently we did not attempt to set formal $N(\text{H I})$ thresholds, except in the particular cases of components showing discernible Lyman α damping wings as described in the sample definitions below. In §8.5 we show how H I column density, as well as metallicity, would influence the derived ionic ratios.

The samples are defined as follows:

sample *sa*—for the statistical studies in §6, includes all C IV, Si IV, C II, Si II and N V lines which fall outside the Lyman forest but limiting Si II only to the strong transition $\lambda 1260$, while excluding all components in the nine systems mentioned in §4.1 showing Lyman α damping wings indicating $N(\text{H I}) \gtrsim 10^{18.7} \text{ cm}^{-2}$ for *any* of its components, namely: $z = 1.927$ in Q1626+6433, $z = 2.438$ in Q1442+2931, $z = 2.761$ in Q1107+4847, $z = 2.904$ in Q0636+6801, $z = 2.770$ and 2.827 in Q1425+6039, $z = 4.031$ in Q1645+5520, $z = 3.317$ in Q1055+4611, and $z = 4.080$ in Q2237–0607 (see Figure 5 and footnotes to Tables 2–10);⁶ used also as the baseline sample in the clustering studies in §7.

sample *sb*—includes all components in sample *sa*; if Si II $\lambda 1260$ is in the forest, adds observed lines of $\lambda\lambda 1304, 1527$ outside the forest; adds strong, unambiguous lines in relatively clear regions of the forest for any of the species except C IV; for the ionization studies in §8 and §9 excludes the systems at $z = 2.827, 3.317$ and 4.080 each showing densely distributed H I absorption collectively having $N(\text{H I}) \gtrsim 2 \times 10^{20} \text{ cm}^{-2}$ (i.e., being in the full “damped Lyman α ” class) while including the other six of the related systems which show milder damping wings centred on very few spe-

cific components, but excludes the latter components to limit self-shielding effects; used without these stated exclusions in the clustering studies in §7 as there indicated.

Sample *sa* contains 887 C IV components in 192 systems and sample *sb*, 1099 C IV components in 201 systems. When specified in §§6–8 we set appropriate column density thresholds to reduce bias due to variations in S/N across the redshift range.

Unless otherwise stated, to avoid significant QSO proximity ionization effects we select systems having velocity $\gtrsim 3000 \text{ km s}^{-1}$ from the nominal redshifts of the background QSOs (Pascarella et al. 2001; Wild et al. 2008). We find no significant differences in our results or conclusions if we extend this limit to 5000 km s^{-1} (§6.1 and §6.2).

6. STATISTICAL PROPERTIES

6.1. Evolution of C IV, Si IV, C II, Si II and N V

The distribution in redshift of the C IV component column densities, $N(\text{C IV})$, for the full sample *sa* is shown in the top panel of Figure 7(a). For each system the values appear as vertical distributions of data points. To avoid confusion in the crowded figures, errors, listed in Tables 2–10, are not indicated in this and subsequent similar figures; mostly these are relatively small. The histogram set in the bottom of the panel shows the aggregated pattern of sightlines covered in redshift outside the Lyman forest to the nine QSOs. The second and third panels similarly show component subsets of the simpler and the more complex systems manifest in the C IV sample, taking systems respectively having numbers $n \leq 6$ and $n \geq 7$ identified components. By these we wish to explore whether our wide observed range fundamentally reflects more than one population. While the precise demarcation we use here is not unique, this nevertheless serves to contrast two indicative groups we choose to compare. We tried populations with combinations of other, similar, values, for example $n \leq 5$ and $n \geq 9$, with insignificant change in outcomes that follow. Finally, the column densities *summed* over each system are displayed in the bottom panel.

The panels in Figure 7(b) give displays for the Si IV, C II, Si II ($\lambda 1260$) and N V component column densities corresponding to the top panel of

⁶The high H I column density may have been a driver for obtaining the spectra of some of these systems. They are excluded from sample *sa* with the aim that this becomes homogeneous.

Figure 7(a) (note the vertical scale shifts for Si IV, Si II and N V relative to C IV). As before, the aggregated coverage in redshift outside the Lyman forest is indicated by the inset histogram for each ion. Within the individual permitted redshift ranges all system components detected in C IV are represented in the other species either as determined values or upper limits. Only Si IV and C II cover the complete redshift range, while Si II and N V are rather poorly sampled. By comparing with C IV it is evident that Si IV and C II are detected preferentially in the *complex* systems (perhaps partly because these are generally the stronger systems) but recall these relate to sample *sa*, not the extended sample *sb* with its additional strong systems and used in §8 and §9. Si II mimics C II quite closely within the redshift intervals in common. For N V, despite the meagre coverage, we note that at the lower redshifts this is detected in most of the few narrow windows available suggesting that *in this range the ion is quite prevalent*, while at higher redshifts there are no detections.

Within the sampling limitations, the general indication of the displays in the two figures is that at least C IV and Si IV are distributed quite uniformly over the observed redshift range. The data for these and the rest of the species, taken as systems, are treated quantitatively in §6.3.

6.2. Absorbers Physically Close to the Sightline QSOs

It is interesting to compare the relative ionization states of absorbers in close physical proximity to the sightline QSOs, excluded from the samples as is defined in §5. We show in Figure 8, in condensed displays corresponding to the top panel in Figure 7(a) and the panels in Figure 7(b), the distribution in redshift of all component species with system velocities $\lesssim 3000 \text{ km s}^{-1}$ from the nominal redshifts of their related QSOs. Over the whole observed range in redshift the character of these results conforms consistently with expectations for gas illuminated by relatively hard radiation: C II and Si II are weak to the extent that they are almost always undetected, and there is relatively strong N V. This is in significant contrast with the presentations in Figures 7(a) and (b). As we show in §8 and §9, at the higher redshifts the radiative environment of the widely distributed strong absorbers not directly influenced by the

sightline QSOs increasingly becomes dominated by much softer spectral contributions from associated galaxies, thus consistent with non-detection of N V.

6.3. Evolution of System Ionic Number Density and Column Density

In Figure 9(a) we display redshift evolution plots for all the observed species in the systems of sample *sa*. As a baseline for all species we select systems having total column density $N_{\text{synt}}(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$, and additionally apply the individual thresholds indicated in the figure for Si IV, C II, Si II and N V. Imposing these thresholds gives close to homogeneous sampling for each ion over the observed redshift range.

Looking first at C IV, the six panels give the total number of systems per unit redshift interval dN_{synt}/dz and the aggregated column density per unit redshift interval dN_{tot}/dz as a function of redshift for the sets of *all*, *simple* and *complex* systems in sample *sa*. The data are corrected for multiple redshift coverage and summed over the adopted bins covered by the horizontal bars. The indicated $\pm 1\sigma$ uncertainties for dN_{synt}/dz are defined by the number of systems in each bin detected above the column density threshold. For dN_{tot}/dz the uncertainties similarly are based on the number of systems present in each bin but now with each system weighted by its total column density, and are dominated by systems with the highest column densities.

To examine the evolution of the number density of systems with redshift, $\mathcal{N}(z)$ ($\equiv dN_{\text{synt}}/dz$), in the comoving volume we use (Misawa et al. 2002)

$$\mathcal{N}(z) = \mathcal{N}_0 \frac{(1+z)^{2+\epsilon}}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}, \quad (2)$$

where \mathcal{N}_0 is the local value of $\mathcal{N}(z)$. If the absorbers have constant comoving volume density and constant proper size then $\epsilon = 0$. Contained in the expression is the Λ CDM cosmology-corrected absorption pathlength interval which for a given redshift interval dz is given by

$$dX = \frac{(1+z)^2}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} dz \quad \Omega = 1. \quad (3)$$

In the left-hand column of C IV panels (dN_{synt}/dz) we show in dotted lines representations of unevolving populations relating to the three data sets and

vertically scaled for easy comparison. It is evident that the data are consistent with *no evolution in number density*. Misawa et al. (2002) using their combined sample EM15 including data from Sargent et al. (1988a) and Steidel (1990) obtain $\epsilon = -1.18$, quite strongly evolving in the sense of increasing number density with cosmic time as the two earlier studies had found (largely with the same data). However, ours is a very sensitive survey of relatively few QSOs but containing a large number of weak systems; the other surveys have much lower spectral resolution and yield only strong systems, with rest-frame equivalent width $W_0 > 0.15 \text{ \AA}$ (implying $N_{\text{sys}}(\text{C IV}) \gtrsim 5 \times 10^{13} \text{ cm}^{-2}$), from nearly an order of magnitude more QSOs yet with a comparable number of systems in the combined sample. Nevertheless, the complex, therefore strong, systems in our sample *sa*, although relatively few in number, show no evolution in number density.

The same form as equation 2 can be used for the comoving total column density of the absorber population by substituting $N(z) (\equiv dN_{\text{tot}}/dz)$ and N_0 . In the corresponding right-hand column of panels we again show in dotted lines representations of unevolving populations. Within the statistical accuracy these data are consistent, also, with *no evolution in total column density*. A difference in evolution between weaker and stronger systems was noticed by Steidel (1990) in his high column density sample but here we find no evidence of this.

The data for Si IV are treated in similar fashion to that described above. The outcome follows a pattern largely resembling that for C IV. Within the statistical accuracy we can again conclude that in number density and column density the data are consistent with an *unevolving population*.

For C II the data are rather limited and the resultant errors are large. Complex systems now strongly dominate the column density population (note the large scale-change in dN_{tot}/dz for the subset of simple systems), consequently the complex and full samples follow closely similar behaviour. While there appears to be a trend of positive evolution with cosmic time both in number density and column density, the significance of these is not high.

The data are even more limited for Si II but indicate an evolutionary trend consistent with that

shown by C II.

N V is sampled yet more poorly in redshift but, at face value, from $z \sim 3$ the data indicate a steep rise in total column density with cosmic time while there is an apparent complete absence of detection at earlier times.

The indicated lack of evolution in C IV and Si IV column density is perhaps surprising: over the extensive redshift range observed, large changes might be expected *a priori* in response to the evolving baryon density and character of the ionizing sources, even for constant metallicity. However, we need to be cautious in interpreting the observations in Figure 9 in this way. As we see later, we are not here taking a freely global view of isolated absorbing regions at large in the cosmos but deal predominantly with *regions closely associated with star-forming galaxies*. This may tend to unify the properties of the absorbing systems despite the large time-spans existing among them. In §8 and §9 we return to this in our full analysis of the ionization conditions exhibited by the individual *components* of the systems in the extended sample *sb*.

6.4. Evolution of C IV and Si IV Mass Density

The comoving C IV mass density is given by (Lanzetta et al. 1991)

$$\Omega_{\text{C IV}}(z) = \frac{H_0 m_{\text{C IV}}}{c \rho_{\text{crit}}} \frac{\sum N_{\text{tot}}(\text{C IV}, z)}{\Delta X(z)}, \quad (4)$$

where $\rho_{\text{crit}} = 1.89 \times 10^{-29} h^2 \text{ g cm}^{-3}$ is the cosmological closure density, $m_{\text{C IV}}$ is the mass of the ion, $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ (we use $h = 0.7$) and $\Delta X(z)$ is the total redshift path over which it is measured. We calculate $\Delta X(z)$ from equation (3) and $\sum N_{\text{tot}}(\text{C IV}, z)$ from the sample indicated in Figure 9(a). The four bins we show for C IV in the figure have mean redshifts $\langle z \rangle = 1.96, 2.65, 3.35, 4.10$. For the full sample (top right panel of the C IV set) we obtain the respective values (1σ uncertainties) $\Omega_{\text{C IV}} = (4.14 \pm 1.74, 3.65 \pm 1.26, 3.26 \pm 0.87, 2.70 \pm 0.89) \times 10^{-8}$. Although there is an apparent mild evolutionary trend, our values are formally consistent with being invariant over the range $1.6 < z < 4.5$. Songaila (2001, 2005) also found a more or less constant trend in the same redshift range. The mean

over the full redshift range of our values above is $\langle\Omega_{\text{C IV}}\rangle = (3.44 \pm 1.24) \times 10^{-8}$ at $\langle z \rangle = 3.05$. D’Odorico et al. (2010) in the range $1.6 < z < 3.6$ find somewhat more of a rise towards lower redshift than ours, but taken together the two trends merge quite well; additionally, D’Odorico et al. (2013) extend their measurements to $z = 6$. Shull et al. (2014) obtain a value at very low redshift and with a large compendium of available literature results trace the evolving progression over $0 \lesssim z \lesssim 6$.

Using the form of equation (4) to do the same for Si IV, the mean redshifts now are $\langle z \rangle = 2.09, 2.65, 3.35, 4.10$, and for the full sample (top right panel of the Si IV set) we obtain the respective values $\Omega_{\text{Si IV}} = (1.44 \pm 0.71, 1.02 \pm 0.50, 0.90 \pm 0.41, 1.57 \pm 0.91) \times 10^{-8}$. Similarly to C IV, these are formally invariant over $1.9 < z < 4.5$. The resultant mean is $\langle\Omega_{\text{Si IV}}\rangle = (1.23 \pm 0.66) \times 10^{-8}$ at $\langle z \rangle = 3.20$. There is good agreement with Songaila (2001, 2005), and again Shull et al. (2014) obtain a value at very low redshift and show available literature results over $0 \lesssim z \lesssim 5.5$.

We show both sets of our data in Figure 9(b). As noted in the previous sub-section, on the understanding that the systems we detect are closely associated with galaxies, we do not probe the metal content of the widespread IGM.

6.5. C IV Component Column Density and Doppler Parameter Distributions

The top panel in Figure 10 shows values presented in the b - $\log N$ plane for all C IV components in sample *sa*, extending over the range $1.6 < z < 4.4$. In the other two panels are the same values separated into the ranges $1.6 < z < 3.1$ and $3.1 < z < 4.4$ (having means $\langle z \rangle 2.51$ and 3.58), dividing the data into roughly equal numbers of components and systems. There is no marked difference between the lower and higher redshift plots except perhaps for a mild extension to higher column densities at lower redshifts.

We note that observational biases are present or potentially present in these data (Rauch et al. 1992). Foremost, the unfilled triangular zone tending to the top left of the diagrams arises because at lower column densities the broader, and therefore shallower, components become relatively more difficult to detect above the noise. Thus, the broad-

est components are detected preferentially at the higher column densities. Relatedly, there is a possible tendency for extremely broad, very weak, components to be masked by more numerous narrower components which, in general, overlap them.

A second possible bias is for the intrinsic narrowness of some lines to be hidden if approaching saturation. This would affect the b -values for the narrower, higher column density components at the bottom right of the diagrams. However, trials showed this is not a significant effect within the range of column densities in our data set.

A potential third effect can be expected from unseparated blends of closely overlapping components which would then appear as single components with larger b -values and higher column densities. While recognising that defining components as entities cannot be an exact process, and that we have aimed to introduce the minimum number of components that justifiably fit the spectral profiles, we judge that beyond our resolution limit such possible blending occurs relatively rarely in our high quality data.

The lower bound in b -value seen in the diagram for these data comes both at about the minimum value resolvable and near the level of thermal broadening for gas at $\sim 10^4$ K. Here we see a small rise in b -value with increasing $N(\text{C IV})$, amounting to $\sim 1 \text{ km s}^{-1}$ over a factor of more than 100 in column density, possibly reflecting the above latter two bias effects at some level. This is somewhat less than the effect noted by Rauch et al. (1996) using a smaller data set.

Below we keep in mind particularly the first of the above bias effects.

Continuing to Figure 11, the left-hand panels show the distributions of $N(\text{C IV})$ and $b(\text{C IV})$ for all components of sample *sa*. Again we compare values for the ranges $1.6 < z < 3.1$ and $3.1 < z < 4.4$ and also separate the simple and complex systems as defined in §6.1. The vertical error bars are $\pm 1\sigma$ values derived from the number in each bin. It is clear, however, that the apparent shapes of these distributions are strongly influenced by the incomplete sampling particularly in the major “exclusion” zone explained above, which severely distorts the true shapes of the distributions. This effect is manifested in $N(\text{C IV})$ by the sharp fall towards smaller column densities

from the apparent peak at $\log N(\text{C IV}) \sim 12.5$. In $b(\text{C IV})$, the presence of a peak and the fall towards smaller values are probably real but the sampling deficiency brings about too-rapid a fall in the distribution extending to larger values.

Confining attention to the better-sampled regions, say $\log N(\text{C IV}) \gtrsim 12.5$ and $b(\text{C IV}) \lesssim 12 \text{ km s}^{-1}$, here we see more quantitatively than in Figure 10 that in our components there is statistically *no discernible bulk change from higher to lower redshifts in the distributions of $N(\text{C IV})$ and $b(\text{C IV})$* , either in aggregate or segregated into simple and complex systems.

6.6. C iv System Column Density and Velocity Spread Distributions

In the right-hand panels of Figure 11 we give histograms similar to those in the left-hand panels but now for the total system C iv column density, $N_{\text{sys}}(\text{C IV})$, and the total spread in *central radial velocity* over all components in a system, $\Delta v_{\text{sys}}(\text{C IV})$ (i.e., not including the widths of the components).

In the consideration of systems it is expected that there be a strong demarcation in properties between simple and complex cases and this is what is seen in the figure. The effect of incomplete sampling of low column density components is more complicated in these cases than for the component distributions just described. On the one hand, the presence or absence of weak components embedded in multi-component systems with relatively high aggregate column densities cannot significantly influence the detection of these systems; on the other, single-component systems clearly mirror the individual component sampling effects; and there are gradations between. Indeed, we note that for $N_{\text{sys}}(\text{C IV})$ the appearance of the fall towards smaller column densities in the simple systems is substantially the same as for the components. For $\Delta v_{\text{sys}}(\text{C IV})$ the effect intrinsically is less direct and the distribution in simple systems is strongly concentrated towards smaller velocity spreads.

But again, here in our data for the systems, there is no discernible change with redshift (at about the 1σ level) in the total or segregated distributions of $N_{\text{sys}}(\text{C IV})$ and $\Delta v_{\text{sys}}(\text{C IV})$.

6.7. C iv System Column Density, Velocity Spread and Number of Components

Figure 12 shows some significant relationships between $N_{\text{sys}}(\text{C IV})$, $\Delta v_{\text{sys}}(\text{C IV})$, and the number of components detected in a system, $n_{\text{sys}}(\text{C IV})$, again comparing values for $1.6 < z < 3.1$ and $3.1 < z < 4.4$. $N_{\text{sys}}(\text{C IV})$ is strongly dependent both on $n_{\text{sys}}(\text{C IV})$ and $\Delta v_{\text{sys}}(\text{C IV})$ and, in turn, there is a strong proportionality between the latter two. Note that in these logarithmic plots, systems with only one detected component (i.e. nominally of zero velocity extent) are excluded in $\Delta v_{\text{sys}}(\text{C IV})$. Petitjean & Bergeron (1994) find similar relationships involving total equivalent width instead of column density. As before, we find no significant systematic change with redshift in any of the relationships.

6.8. C iv Component and System Differential Column Density Distributions

Figure 13 gives the C iv differential column density distribution function $f(N, X)$ both for the individual components and the systems, each for the same two redshift subsets as before and here also shown for the full range (shown *dotted*). The function $f(N, X)$ gives the number of absorbers per unit column density per unit absorption pathlength, $d^2N/dNdX$ (accounting for the multiple redshift coverage from the different sightlines), where the ΛCDM cosmology-corrected absorption pathlength interval X is given by equation 3. The data are summed over the bin size $10^{0.3}N$ as shown, with vertical error bars of $\pm 1\sigma$ values derived from the number of absorbers in each bin.

First, for the components, the incompleteness at low column densities seen in Figure 10 causes the turnover below $N \sim 10^{12.5} \text{ cm}^{-2}$ but otherwise the distributions can be approximated as a power-law $f(N, X) \propto N^{-\beta}$ up to $N \sim 10^{14} \text{ cm}^{-2}$, after which the observations become increasingly more uncertain because in our sample very few individual components have higher column density. As found above with other quantities, there is little significant difference between the slopes for the two redshift subsets. We therefore use the combined set and above the completeness limit obtain $\beta = 2.36 \pm 0.10$ and show this in the figure. For

a lower resolution sample with $\langle z \rangle = 2.65$ and extending to $N \sim 10^{14} \text{ cm}^{-2}$ Petitjean & Bergeron (1994) obtain $\beta = 1.64 \pm 0.10$.

For the systems, in similar fashion, we obtain $\beta = 1.68 \pm 0.09$ for the combined set as shown. With sparser data Ellison et al. (2000) obtain $\beta = 1.44 \pm 0.05$ near $z = 3.2$, Songaila (2001) from a large sample having $N_{\text{syst}} > 10^{13} \text{ cm}^{-2}$ over the range $1.5 \lesssim z \lesssim 4.5$ finds her data consistent with $\beta = 1.8 \pm 0.10$, D’Odorico et al. (2010) obtain $\beta = 1.71 \pm 0.07$ over the range $1.6 < z < 3.6$ and D’Odorico et al. (2013) in three redshift intervals extending over $2.5 < z < 6.2$ obtain an average value $\beta = 1.70 \pm 0.08$.

It is interesting that for H I lines in the Lyman forest, values quite similar to the latter are found over column densities $N(\text{H I}) \sim 10^{14.0-17.0} \text{ cm}^{-2}$, e.g., $\beta = 1.75 \pm 0.15$ for $z > 1.5$ (Kim et al. 2002b), $\beta = 1.60 \pm 0.03$ for $z = 0.5-1.9$ (Janknecht et al. 2006), $\beta = 1.650 \pm 0.017$ for $z = 2-3$ (Rudie et al. 2013).

7. C IV COMPONENT AND SYSTEM CLUSTERING

7.1. Two-Point Velocity Correlation Function

Many past studies of the two-point correlation function show that C IV components cluster strongly on velocity scales $\lesssim 200 \text{ km s}^{-1}$, with significant clustering out to a few 100 km s^{-1} more (Sargent et al. 1980; Young et al. 1982; Sargent et al. 1988a; Petitjean & Bergeron 1994; Rauch et al. 1996; Womble et al. 1996). In some cases clustering extends to scales of order $1000-10000 \text{ km s}^{-1}$ and this can be traced to a few unusually complex groups of systems (Sargent & Steidel 1987; Heisler et al. 1989; Dinshaw & Impey 1996; Quashnock et al. 1996; Scannapieco et al. 2006). Clustering similar to that observed in C IV is measured in Mg II and other ions (Sargent et al. 1988b; Petitjean & Bergeron 1990; Steidel & Sargent 1992; Charlton & Churchill 1998; Churchill et al. 2003; Scannapieco et al. 2006). It is suggested that the clustering signal reflects either galaxy clustering, clustering of clouds within the same galactic halo, or a combination of the two. The issue is complicated by the wide disparity in velocity resolution and sample size among the different observations. The clustering seen in metals seems to

contrast with that observed in H I which in general shows no significant clustering signal (Sargent et al. 1980; Rauch et al. 1992), or comparatively weak clustering (McDonald et al. 2000) and accentuated at larger column densities (Cristiani et al. 1997). However, as already raised in §5, in H I much of the small-scale structure is obscured by unresolved blending of overlapping velocity components due to the greater thermal broadening (Fernández-Soto et al. 1996) and often saturated absorption profiles.⁷ Below we return to this apparent contrast in clustering properties.

In Figure 14 we give velocity two-point correlation functions (TPCF) for the C IV absorbers. In the standard manner these are normalized to the expected number of pairs per bin computed for a set of random distributions in redshift space matching the individual wavelength ranges and number of C IV absorbers observed for each of the nine QSOs in the sample. The simulated randomly distributed absorbers are collated by pairwise velocity separation in 1000 realizations and compared with the distribution of velocity separations in the data to derive the correlation

$$\xi(\Delta v) = \frac{N_{\text{data}}(\Delta v)}{N_{\text{random}}(\Delta v)} - 1, \quad (5)$$

where Δv is the velocity in km s^{-1} of one cloud as measured by an observer in the rest frame of the other.

In the top panel of the figure we show the result for the individual C IV components of sample *sa* (here without a column density threshold limit) spanning the total range $1.6 < z < 4.4$, with velocity resolution 15 km s^{-1} for $\Delta v < 370 \text{ km s}^{-1}$ and 20 km s^{-1} for $\Delta v > 370$. The data points indicate the middle of the bins, with the first bin excluded because its width is comparable with the velocity width of the C IV components. The $\pm 1\sigma$ errors in the simulated random distribution are smaller than the data points shown. Following the usual pattern, the clustering signal in our data is strong at small velocity separations and declines steeply with increasing separation. The velocity correlation length, defined as the pair separation

⁷In Figure 4 the H I profiles we show are selected by detection of associated C IV absorption and generally are stronger and more complex than the majority of the forest lines.

for which $\xi(\Delta v_0) = 1$, is $v_0 = 230 \text{ km s}^{-1}$, with significant signal extending only to $\sim 300 \text{ km s}^{-1}$.

The second panel gives the result for all components of sample *sb* (see §5 for the specific inclusions). As mentioned in §5 this larger sample may be statistically less homogeneous than *sa*. The resultant profile is somewhat lumpier than for sample *sa*, now having $v_0 = 330 \text{ km s}^{-1}$ and significant signal extending to $\sim 400 \text{ km s}^{-1}$. The increase in Δv relative to sample *sa* is consistent with the generally large velocity widths and richness of the added highly complex systems (see Tables 2–10).

Structure similar to that for sample *sb* is found for C IV mixed samples at intermediate and high redshifts in earlier studies (Petitjean & Bergeron 1994; Songaila & Cowie 1996; Womble et al. 1996; Rauch et al. 1996) and more recently by Scannapieco et al. (2006). Petitjean & Bergeron fit the shape of the TPCF by using two Gaussians, obtaining a best fit with velocity dispersions $\sigma = 109$ and 525 km s^{-1} for their full sample and $\sigma = 95$ and 450 km s^{-1} for a selected subset. With a higher resolution sample Rauch et al. (1996) find need for a three-component Gaussian fit with $\sigma = 22, 136$ and 300 km s^{-1} . Following the same procedure for our samples *sa* and *sb*, we parameterize the TPCF as a multi-component Gaussian

$$\xi(\Delta v) = A_1 \exp\left(-\frac{\Delta v^2}{2\sigma_1^2}\right) + A_2 \exp\left(-\frac{\Delta v^2}{2\sigma_2^2}\right) \dots, \quad (6)$$

where A_n is the amplitude of the n^{th} component; the results are shown in the figure. First, for *sa*, we achieve a very good two-component fit with $\sigma_1 = 35.5 \text{ km s}^{-1}$, $A_1 = 8.8$, $\sigma_2 = 105 \text{ km s}^{-1}$, $A_2 = 11.6$. A one-component fit is ruled out and more than two components is unnecessary. For *sb* we obtain a very good three-component fit, with a narrow component identical in width to that in *sa*, $\sigma_1 = 35.5 \text{ km s}^{-1}$, but with $A_1 = 5.0$, and the others with $\sigma_2 = 80 \text{ km s}^{-1}$, $A_2 = 9.5$, $\sigma_3 = 185 \text{ km s}^{-1}$, $A_3 = 6.5$.

The set of three remaining panels in the figure gives results for the data treated as *systems*; here the $\pm 1\sigma$ errors in the random distributions (significantly larger than for the components because of the smaller numbers) are shown by *bounding thin lines*. In the first panel of this set, the result obtained using the 201 system redshifts for sample *sb*

with velocity resolution 500 km s^{-1} and extending to $\Delta v = 12,000 \text{ km s}^{-1}$ is shown on an expanded vertical scale. The TPCF is notably flat over the whole range of separations, demonstrating clearly that the *systems* of C IV absorption lines *in our sample* are randomly distributed. Using the purer sample *sa* gives an almost identical result because the relatively few highly complex systems in sample *sb* contribute to the total each with the same weight as do the rest of the systems (we give the *sb* case to demonstrate that this result is not specific to sample *sa*). We find the same pattern for velocity resolutions below 500 km s^{-1} as well as up to several 1000 km s^{-1} and for Δv as large as $50,000 \text{ km s}^{-1}$. The large-scale example is in the second panel of the set and in the bottom panel is a subset of the sample in which we include only the 146 systems having velocity spread $\Delta v_{\text{syst}}(\text{C IV}) < 150 \text{ km s}^{-1}$ and use velocity resolution 150 km s^{-1} . In all cases the result is indistinguishable from a *random distribution*.

We point out here that our approach to identifying systems is based on the observed physical separation between *groups of closely associated components* in our samples. These include some with quite complex structures having a wide spread in velocity and which well reflect the strong absorbers closely related to *individual galaxies* as we discuss in §7.3. Scannapieco et al. (2006) take a different approach, defining a velocity linking length v_{link} and grouping together into *nominal* systems all components whose separation from their nearest neighbour is less than v_{link} , using values 25, 50 and 100 km s^{-1} . In this way they find little difference between system and component correlation functions. Such v_{link} lengths are considerably shorter than the overall widths of most of the complex groups we identify (see the vertical associations in Figure 7 and the plots in Figures 11 and 12), suggesting that in such cases the v_{link} technique acts in effect as a smoothing process resulting in data of lower velocity resolution while nevertheless reflecting structure within the complex associations that shows up in the *component* correlation but for which in the *system* correlation we here count each as one unit like any other. Furthermore, the majority of members in our system sample have velocity width $< 100 \text{ km s}^{-1}$ so might fortuitously act in the v_{link} regime, yet we find no contributing signal to system clustering.

In measurements similar to ours Fathivavsari et al. (2013) also find no evidence of system clustering (see §7.4).

Briefly summarizing, for *components*, although the detailed shape of the TPCF depends on the specific contents of the samples used, we observe that broadly the results are similar. Our large, high quality sample *sa* gives better statistical definition than before and by exclusion of the few systems containing significant Lyman α damping wings (present in sample *sa*) we regard this as representing the “normal” great majority of C IV absorbing systems. With this sample of components we obtain a more compact TPCF than in most other work. Specifically, the shape of our observed TPCF does not require Gaussian elements as broad as those found by Petitjean & Bergeron (1994) or Rauch et al. (1996). Churchill et al. (2003) come to a similar conclusion for Mg II absorbing clouds. Now for *systems*, most importantly in both of our samples we see no evidence of clustering *on any scale* from Δv as small as 150 km s⁻¹, where the general *component* clustering signal is still strong, out to very large separation values (we return to this in §7.4).

7.2. Comparison with Galaxy Clustering

It seems that for our component samples in the top two panels of Figure 14 the TPCF has a common narrow core component, with broader components whose characteristics depend on the precise definition of the sample. While this might give a clue to the dynamical makeup of the absorber population we should bear in mind that this is a contrived description of the TPCF (in some cases we find an exponential fit is almost as good).

For galaxies, the TPCF is a simple, fundamental statistic of the galaxy distribution. Estimations of *real-space* galaxy clustering yield a TPCF very close to power-law form over a broad range of scales (Loveday et al. 1995; Zehavi et al. 2002; Hawkins et al. 2003), although on detailed examination this is seen to be largely fortuitous (Zehavi et al. 2004). The parameters of the power-law depend on the characteristics of the sample galaxies and dominantly on their luminosity (Norberg et al. 2002). On the other hand, galaxy clustering in *redshift-space* is strongly affected by gravitationally induced distortions. On small scales, random peculiar velocities will cause clustering to

be underestimated, while on large scales coherent infalling bulk flows will lead to an overestimate of the clustering amplitude (Kaiser 1987). Consequently, the form of the redshift-space TPCF departs considerably from a simple power-law (Zehavi et al. 2002; Hawkins et al. 2003). Large scale Λ CDM simulations show good correspondence with the observed galaxy clustering (Benson et al. 2001; Weinberg et al. 2004). In particular, these simulations predict remarkably little comoving clustering evolution from high redshifts to the present epoch (although the underlying dark matter clustering evolves strongly).

The two-component Gaussian fit to the *component* TPCF for sample *sa* given in the top panel of Figure 14 is reproduced in logarithmic form in Figure 15. The stepped horizontal lines in the figure give the *system* TPCF $+1\sigma$ bin errors from the bottom set of three panels of Figure 14, taken as upper limits, in to 500 km s⁻¹ from the first panel then to 150 km s⁻¹ from the third. We convert the velocity scale for our full sample at $\langle z \rangle = 3.0$ to h^{-1} comoving Mpc using Hubble constant h in units of 100 km s⁻¹ Mpc⁻¹ and show this at the top of the figure for comparison with the galaxy estimations. The two differently-scaled *short-long dashed lines* are results from the large 2dF Galaxy Redshift Survey (Hawkins et al. 2003) for the galaxy real-space TPCF as fitted by the power-law $(r/r_0)^{-\gamma_r}$ with $r_0 = 5.05h^{-1}$ Mpc, $\gamma_r = 1.67$ and the corresponding redshift-space TPCF as fitted piecewise by the power-law $(s/s_0)^{-\gamma_s}$ with $s_0 = 13h^{-1}$ Mpc, $\gamma_s = 0.75$ at small scales, and $s_0 = 6.82h^{-1}$ Mpc, $\gamma_s = 1.57$ around s_0 . The *dotted line* is the best-fit correlation function to the angular clustering at $z = 2.94$ of Lyman-break galaxies, with power-law parameters $r_0 = 4.0h^{-1}$ Mpc, $\gamma_r = 1.57$ (Adelberger et al. 2005a).

Figure 15 shows that above $\Delta v \sim 150$ km s⁻¹ the *one-dimensional* TPCF for the C IV *components* dips significantly below the TPCF found for galaxy clustering. In addition, the lack of significant absorber *system* clustering observed above $\Delta v = 150$ km s⁻¹ gives a very substantial deficit in clustering amplitude relative to galaxies out to $\Delta v \sim 1000$ km s⁻¹.

7.3. Absorbers and Galaxies

To complete the picture we now consider observations associating absorbers with galaxies. Attempts to establish directly how metal absorption systems and galaxies are connected initially focused on searches for galaxies near the line of sight to QSOs with redshifts closely similar to the absorbers (Boksenberg & Sargent 1978; Bergeron & Boissé 1991; Steidel et al. 1994; Le Brun et al. 1997; Steidel et al. 2002). Most work of this kind was done at $z \lesssim 1$ for relatively strong systems selected by the presence of Mg II and associated with gas having $N(\text{H I}) \gtrsim 10^{17} \text{ cm}^{-2}$ (i.e., Lyman limit systems). Investigating the kinematical properties of several such cases with projected impact parameter $20 \lesssim d \lesssim 100$ proper kpc Steidel et al. (2002) find the identified galaxies to be relatively normal spirals, with circular velocities $100 \leq v_c \leq 260 \text{ km s}^{-1}$. While the absorber characteristics are consistent with rotation being dominant also for the absorbing gas, the total range of velocities, typically 200–300 km s^{-1} , and their placing to one side of the galaxy systemic redshift, is not consistent with simple disc rotation viewed along a single sightline.⁸ Steidel et al. (2002) suggest that models to explain their observations require either extremely thick rotating gas layers, rotation velocities that vary with height above the extrapolated galactic plane, or a combination of both, with rotational motion dominating over radial infall or outflow even for gas well out of the galactic plane. The kinematics of the absorbing gas observed in damped Lyman α systems (DLA) similarly appears consistent with rotating thick disc geometries (Prochaska & Wolfe 1998) although not uniquely so (Haehnelt et al. 1998; Ledoux et al. 1998; McDonald & Miralda-Escudé 1999), but there is difficulty reconciling the high ionization species with the low in the same model (Wolfe & Prochaska 2000). Extending to higher redshifts, from a large sample of Mg II absorbers Ménard et al. (2011) find a strong correlation of associated [O II] luminosity, an estimator of star formation rate, while the velocity structure of some

of the strongest Mg II absorbers is suggestive of superwinds arising in actively star-forming galaxies (Bond et al. 2001) and more generally there is evidence for the importance of large-scale galactic winds (Pettini et al. 2001). C IV absorption kinematically is strongly correlated with Mg II and usually extends more widely in velocity (Churchill et al. 2001), and at high redshifts complex C IV absorption systems are observed commonly to co-exist with galaxies (e.g., Adelberger et al. 2003, 2005; Steidel et al. 2010; Martin et al. 2010). We address the latter more fully in §8 and §9.

7.4. Conclusions on the Clustering Properties of Metal Absorbers

In the light of observations linking Mg II and C IV absorption systems with specific galaxies close in line of sight to the background QSOs, and the fact that these systems have extended kinematic structure of a few 100 km s^{-1} similar to the C IV systems in our samples, it seems inescapable that our velocity correlation results for the absorption *components* in sample *sa*, contrasting with the lack of *system* clustering, are entirely due to the peculiar velocities of the gas present in the outer extensions or circumgalactic media (CGM) of individual galaxies, *not to general galaxy-galaxy clustering*. This conclusion is not changed when we substitute the component sample *sb* with its bias to highly complex systems. The different broader components of the distributions we find in the multi-Gaussian fits to the shape of the TPCF in the cases we show in Figure 14 presumably reflect the distribution of the more disturbed cases of outflow into the extended regions probed, while the narrow components of the distributions may indicate underlying, more quiescent, motion. Charlton & Churchill (1998) concluded with a similar picture in their study of Mg II absorbers.

The explanation for the observed lack of *system* clustering in our C IV sample, while the systems are known to be associated with galaxies, then must be simply geometrical selection. In conventional clustering studies all related galaxies in the plane of the sky are included (with defined sample specifications) and the spatial variance is completely sampled in two or three dimensions on all scales. The situation for the one-dimensional sightline available to each background QSO, although highly extended in redshift, is quite differ-

⁸The expectation that a sightline through a galaxy at large radius would show only a small differential rotational velocity, contrary to the observed velocity spread of the absorption systems, earlier had counted against the idea that the velocity structure in the systems is due to motions associated with single galaxies (Sargent et al. 1988a).

ent. In this case the galaxy population is probed so sparsely that it is a rare occurrence for the gaseous extent of more than one galaxy to be encountered in a given cluster or group.

The lack of system clustering in our sample implies *there is no obvious observational distinction between the clustering of metal systems and strong absorbers of the Lyman α forest*. Because any complex component structure in H I is largely hidden by thermal broadening and saturation, the H I absorption lines effectively are counted as *systems* like the C IV systems. However, the far more numerous weaker H I lines probe to much lower densities in the intergalactic medium, so do not represent the same population as the observed metal systems which in general are more directly associated with galaxies.

Highly extended correlated structures would appear when a sightline fortuitously passes along a large-scale filamentary or sheetlike distribution of galaxies in a supercluster, bringing about a rich complex of absorber systems well extended in redshift, but the incidence of such occurrences is low. Rauch et al. (1996) consider a less extreme version of such a model to explain the tail of the TPCF found in their smaller C IV sample, interpreting this as a Hubble flow velocity extension. On the other hand, Simcoe et al. (2002) find that for the components of a limited sample (12) of O VI systems tracing the warm-hot intergalactic medium the velocity TPCF is similar to the spatial power-law form seen for galaxies, with a comoving correlation length $\sim 7h^{-1}$ Mpc. They conclude that for this population the signal is dominated by large-scale structure. We stress again, however, that in the present work we seek to characterize the “normal” situation obtaining for the large bulk of relatively weaker metal absorption systems in the cooler phase identified by C IV. In this respect our work is different from large-scale studies using samples only of strong C IV systems. Quashnock et al. (1996) use 373 QSO sightlines having a total of 360 strong C IV absorption systems covering the redshift range 1.2–4.5; in contrast, our sample has an average of about 20 systems per sightline. With a velocity resolution of about 600 km s^{-1} they find weak clustering, $\xi \sim 0.4$, on scales of superclusters, with significant signal contributed by groups of absorbers in only 7 of the sightlines. Quashnock & Vanden Berk (1998) extend this study to

smaller scales using velocity resolution 180 km s^{-1} and a restricted sample of 260 strong C IV systems drawn from 202 sightlines, finding significant clustering of power-law form on scales of clusters and superclusters. It is interesting that Fathivavsari et al. (2013) in a high velocity resolution investigation towards the QSO PKS 0237-233, a line of sight known to intersect highly untypical complex groups of strong absorbing systems and interpreted as revealing the presence of a supercluster of galaxies, in fact find no *system* clustering at all and obtain displays very similar to those we show in Figure 14.

Our sample of numerous relatively weak C IV systems in few sightlines does not probe well such large-scale structure. Nor, as we have seen, do our systems strongly sample galaxies within clusters. Our high velocity resolution data perform the complimentary role of finely probing the environment in the vicinities of *individual* galaxies.

8. IONIZATION BALANCE

8.1. Evolution of Ionic Ratios Si IV/C IV, C II/C IV, Si II/Si IV, Si II/C II, N V/C IV

In Figure 16(a) we give the distribution in redshift of the observed column density ratios Si IV/C IV for absorbers of sample *sb* (for this and the related quantities below see §5 for the specific inclusions used here) but restricted to those in which Si IV is potentially accessible. The different symbols indicate specific sub-sets of the data listed in Tables 2–10 relating to sample *sb* and are identified in the caption. Like in Figure 7(a), here we show *component* values for the full sample and separately the simple and the complex systems, with again the obvious vertical associations indicating members of the same system, and in a fourth panel show values summed over each *system*. The upper limits indicate values in which Si IV is undetected. In all these cases we now take $N(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$ as an acceptance threshold. The accompanying panels on the right give the corresponding median values obtained over the redshift spans defined by the horizontal bars, with indicated uncertainties obtained as 1σ bootstrap values. Unlike the single-species distributions in Figure 7(a), here we do not need to correct for multiple redshift coverage because each component or

system ionic ratio value represents an independent measure of absorber ionization *balance* (although incomplete, as we explain later). The upper limits shown in the data panels are included in the assessment of median values; the occasional high upper limits coming above the level of the derived median value here do not significantly influence the accuracy of the results.

It is striking that within the small uncertainties the component values for the full sample *sb* of Si IV/C IV are shown to be *constant over the whole observed range* $1.9 < z < 4.4$. For the simple systems there is a significant continuous fall in the median with cosmic time, by ~ 0.4 dex over the observed range, while the complex systems, containing the bulk of the fully detected components, remain consistently invariant.

The system ionic ratios in the bottom of the figure are obtained after first separately summing the individual Si IV and C IV component values in each system. Once again, there is no detectable change in the median over $1.9 < z < 4.4$. Although we have earlier commented on the shortcomings of using total system values for ionic ratio determinations we include these results for comparison with work by Songaila & Cowie (1996) and Songaila (1998, 2005) who argue that their observed evolution of Si IV/C IV, which shows a substantial jump in the median at $z \sim 3$, points to a sudden hardening of the ionizing background that is consistent with an abrupt reduction in the opacity of the evolving IGM to He II ionizing photons as He II completely reionizes to He III. We previously report the lack of such a jump (Boksenberg 1997; Boksenberg et al. 2001, 2003), also concluded by Kim et al. (2002a) and Aguirre et al. (2004), and reiterate this here (see also D’Odorico et al. (2013) for extension to higher redshifts). Because of the He II high ionization threshold (54.4 eV) and small photoionization cross-section coupled with the rapid recombination rate of He III, the double ionization of He is expected to lag far behind the ionization of H I and He I and be fully completed only at $z \sim 3$ by QSOs approaching the peak of their activity (e.g., Madau et al. 1999; Sokasian et al. 2002; McQuinn et al. 2009). Several workers find support more directly than above for high He II opacity in the intergalactic medium at $z \gtrsim 3$ (Reimers et al. 1997; Heap et al. 2000; Kriss et al. 2001; Smette et al. 2002; Shull et al.

2010; Syphers & Shull 2013). Schaye et al. (2000b) and Theuns et al. (2002) show that He II reionization at $z \sim 3.5$ results in an increase by a factor 2 in the temperature of the intergalactic medium at the mean density and find evidence for such a jump from observations of Lyman α forest lines. However, analyses by McDonald et al. (2001) and Zaldarriaga et al. (2001) do not show a significant temperature change at these redshifts, although the temperatures they find are higher than expected for photoionized gas in ionization equilibrium with cosmic background radiation and can be explained by gradual additional heating due to *ongoing* He II reionization, reflected also in more recent measurements (Becker et al. 2011, 2013; Pâris et al. 2011). Notwithstanding, use simply of the column density ratio Si IV/C IV to measure the influence of He II ionizing radiation on the absorbers has significant limitations and we do not make any claims concerning the evolution of the ambient ionizing spectrum based on Figure 16(a) alone. We consider He II reionization further in respect of our fuller interpretation of the ionization measurements coming in §8.2.

Again following the pattern of Figure 7(a) and (b), displays corresponding to the panel at the top of Figure 16(a) are given in Figure 16(b) for the component column density ratios C II/C IV, Si II/Si IV, Si II/C II and N V/C IV, although here for the first and fourth of these there is somewhat more uncertainty in the median values arising from included upper limits. C II/C IV shows a mild progressive rise with cosmic time by ~ 0.4 dex over $3.7 < z < 1.9$, although here not far from the flatter distribution of median values found by Songaila (2005). Si II/Si IV shows a steeper trend in the same direction, rising by ~ 0.7 dex over this range, while Si II/C II appears quite flat, although in both cases the data are rather sparse. N V/C IV is relatively flat from $z \sim 3.2$ to lower redshifts, while to higher redshifts, within the limited data allowed by the available narrow windows, only upper limit values are obtained. As we earlier commented for Figure 7(b) using sample *sa*, it is similarly evident here that the ionic ratios in Figure 16(b) using the enhanced sample *sb* (see §5) are detected preferentially in the strong, *complex* systems identified among the Si IV/C IV displays in Figure 16(a).

Although at this stage some collective infer-

ences might be made about the radiation environment from the data in Figure 16(a) and (b), the fact remains that individual ionic ratios give only partial evidence of ionization state. Therefore we move on instead to use combinations of these ratios as more complete indicators from which to derive information on the evolution of the ionizing spectral energy distribution as experienced by the absorbers.

8.2. Evolution of Ionic Ratio Combinations and Comparison with Models of Absorbers Ionized by the Cosmic UV/X-Ray Background

We consider the combination of column density ratios $\text{Si IV}/\text{C IV} : \text{C II}/\text{C IV}$, $\text{N V}/\text{C IV} : \text{C II}/\text{C IV}$, $\text{Si II}/\text{Si IV} : \text{C II}/\text{C IV}$ and $\text{Si II}/\text{C II} : \text{C II}/\text{C IV}$. To compare our observations with model ionization predictions we simulate the conditions in our absorbers by means of the CLOUDY code version C10 (Ferland et al. 1998, 2011)⁹ for one-sided illumination of a plane-parallel slab of gas. For the radiant exposure we begin with the metagalactic ionizing background synthesised by the cosmological radiative transfer code introduced by Haardt & Madau (1996) and recently substantially updated (Haardt & Madau 2012), which gives the evolving ionizing radiation from QSOs and star-forming galaxies propagating in a clumpy, primordial IGM. Here, for detailed reference useful in our further developments below, we give an outline of the model radiative inputs from Haardt & Madau (2012).¹⁰

The QSO emissivity contains: (i) an optical-ultraviolet component for radio-quiet QSOs with spectral energy distribution given by a power law of form $F_\nu \propto \nu^{-1.57}$ extending from 1300 Å to shorter wavelengths (Telfer et al. 2002) covering the ionizing range of interest here, with comoving emissivity at 1 Ryd closely fitting the results of Hopkins et al. (2007); and (ii) an X-ray component with contributions accounting in detail for the observed cosmological X-ray background. The

underlying assumption for the ionization state of the IGM is photoionization equilibrium in a pure H+He gas. To account for the effective opacity of the IGM the new code uses a piecewise power-law parameterization of the distribution in redshift and column density of intergalactic absorbers that fits recent measurements of the Lyman continuum mean free path of 1 Ryd photons (Prochaska et al. 2009) as well as the observed effective Lyman α optical depth (Faucher-Giguère et al. 2008; Fan et al. 2006), and together covering the redshift range concerning the observations in this paper. Firstly, in the panels of Figure 17(a), for reference we give spectral displays of the metagalactic radiation background if QSOs are the only contributing sources, (Q_{HM}), shown in *dashed lines* at the specific redshifts $z_{HM} = 1.9, 2.6, 3.4, 4.4$, bounding the sample redshift intervals we select for our data in the three panels of the figure.¹¹ We focus on the frequency range effective for photoionization of the relevant species in our absorbers, and identify the positions of the significant ionization thresholds. The spectra contain the sawtooth modulation produced by resonant absorption in the Lyman series of intergalactic He II (Madau & Haardt 2009), not included in earlier versions, which becomes significant at $z \gtrsim 3$. The analogous modulation produced by the H I Lyman series becomes significant only at $z \gtrsim 6$. In our CLOUDY computations below we add the cosmic microwave background pertaining to each redshift to account for Compton cooling of the absorbers, which becomes mildly significant at low densities at our highest redshifts but otherwise has negligible effect. This background is not included in the Haardt & Madau (2012) radiative transfer computations.

While QSOs play a dominant role as sources of ionizing radiation over a wide band of energies at $z \lesssim 3$, to higher redshifts their strongly declining population coupled with the rapid build-up of star-forming galaxies brings the latter to be the dominant sources of hydrogen-ionizing radiation in the reionization of the IGM from early times. To compute the evolving Lyman continuum emissivity from galaxies at all epochs Haardt & Madau start with an empirical determination of the star

⁹We find the use in our application of the later version C13 makes very little change indeed to the results presented in this paper.

¹⁰Haardt & Madau (2012) use the intensity J_ν (erg s⁻¹ cm⁻² Hz⁻¹ sr⁻¹) but here to accommodate the requirement of one-sided illumination in our CLOUDY modeling we use $F_\nu = 4\pi J_\nu$ and to avoid directional effects work basically with absorber regimes optically thin in the Lyman continuum.

¹¹We are grateful to have this specially provided (Haardt 2014).

formation history of the Universe to obtain the redshift-dependent, dust-reddened, galaxy far-UV (1500 Å) luminosity density. After correction for dust attenuation using a Calzetti et al. (2000) extinction law this is compared with results of evolving spectral population synthesis models using the GALAXEV library (Bruzual & Charlot 2003) for a Salpeter (1955) initial mass function (IMF) covering 0.1–100 M_{\odot} and a metal-enrichment law of decreasing metallicity with redshift according to the expression $Z(z) = Z_{\odot} 10^{-0.15z}$ (Kewley & Kobulnicky 2007), while adjusting the star formation rate density iteratively until the computed far-UV luminosity density as a function of redshift achieves a good match to related observational data. Stellar synthesis models then are used again to compute the evolving frequency-dependent UV emissivity (i) dust-reddened at all photon energies below 1 Ryd, and (ii) following a luminosity-weighted escape fraction of hydrogen-ionizing radiation ($\langle f_{esc} \rangle$) that is constant over all energies between 1 and 4 Ryd. In this treatment $\langle f_{esc} \rangle$ is a free parameter that represents the proportion of ionizing radiation leaking into the IGM from star-forming galaxies and here assumed as emanating not from sources in a semiopaque medium but from *a small fraction of essentially unobscured sources* (Gnedin et al. 2008).¹² The form of the escape fraction, given as

$$\langle f_{esc} \rangle = 1.8 \times 10^{-4} (1 + z)^{3.4} \quad (7)$$

(refer also to: Inoue et al. 2006; Boutsia et al. 2011), is a steeply rising function of redshift *dictated* by the need to reproduce the hydrogen-ionization rates obtained from flux-decrement

¹²It is important to note that this is an *absolute* escape fraction, being the ratio of escaping Lyman continuum flux to the intrinsic flux emitted in the same spectral region by the stars in the galaxy. Observationally this ionizing escape fraction is usually assessed relative to the readily-accessible flux at rest-frame 1500 Å (or a nearby wavelength) in the non-ionizing far-ultraviolet, corrected for attenuation by dust, then used to obtain the intrinsic stellar Lyman continuum flux from spectral synthesis models with which finally to compare the level of observed Lyman continuum radiation (here also with correction for the average IGM opacity) and so obtain the escape fraction (Steidel et al. 2001; Shapley et al. 2006). If there is insufficient observational evidence to determine the dust attenuation a *relative* escape fraction is taken simply as the ratio of escaping Lyman continuum radiation to the escaping radiation at 1500 Å (Steidel et al. 2001).

measurements over $z = 2\text{--}5$ and to compensate for the decline in the star formation rate density to higher redshifts sufficient to enable reionization of the IGM at early enough epochs (and consistent with *WMAP* results), and is made zero at energies above 4 Ryd.

We use this expression throughout the rest of the paper in our empirical investigations of the escape *process* and therefore it is important to point out that in this “minimal cosmic reionization model” the measurements included by Haardt & Madau (2012), and to which there is a good fit by equation 7 *over the stated range in redshift*, are *independent* of the actual mode of escape so apply equally well to the work we describe later. While Haardt & Madau make clear that the escape fraction cannot be certain on the large scale in redshift we stress that our range of consideration $1.9 < z < 4.4$ shown in Figure 17 and others later is coincident with the region based on solid determinations of hydrogen-ionization rates. Indeed, Kollmeier et al. (2014) recently find a large mismatch between the result from similar observations at very low redshift by the Hubble Space Telescope Cosmic Origins Spectrograph and the prediction of equation (7), but at the same time stress the excellent agreement obtained for $z = 2\text{--}5$, which covers our range of interest here. Recent flux-decrement measurements at high redshifts (Becker & Bolton 2013) indicate a relative increase in hydrogen-ionization rate over those implied in equation (7), starting from $z \sim 3.5$ and rising to a factor 2 ± 1 at $z = 4.4$. While recognizing this, for our indicative purposes in this paper we can adequately stay with equation (7) both for the metagalactic background values here and in our additional work that follows in this paper.

In Figure 17(a) we add, in *continuous lines*, spectral displays for the full QSO+galaxy (Q_{GHM}) metagalactic radiation background. The respective values of the flux F_{ν} (erg s^{−1} cm^{−2} Hz^{−1}) at the H I Lyman limit (1 Ryd, i.e., 912 Å) at the redshifts z_{HM} 1.9, 2.6, 3.4, 4.4 are numerically: 4.02×10^{-21} , 4.02×10^{-21} , 3.02×10^{-21} , 2.10×10^{-21} . Contrasting with the Q_{HM} model, the Q_{GHM} spectral intensity is highly raised at energies below the H I ionization edge where the galactic radiation makes a strong contribution,¹³

¹³Note that in the context of this paper spectral radiation

while beyond this edge there is a large depression of the galaxy spectrum reflecting the imposed small escape fraction and extending to the He II ionization edge at which the galaxy contribution is truncated. From the He II edge to higher energies the further depression to below the Q_{HM} intensity levels, a strong function of redshift, is due to the increased He II continuum opacity through the changed ionization balance of the IGM resulting from the large increase in the H-ionizing emissivity from the early galaxy population but here unaccompanied by a similar increase at the He II edge.

To typify the general state of the absorbing regions (e.g., Simcoe et al. 2002, 2006) we assume a low metallicity gas optically thin in the H I Lyman continuum and adopt the nominal properties $Z = 0.003$ solar (i.e., $[Z] = -2.5$)¹⁴ and neutral hydrogen column density $N(\text{H I}) = 10^{15} \text{ cm}^{-2}$. We take these values for illustration and here do not imply that precisely these are demanded by the observations: in §8.5 we explore the sensitivity of the model results to these parameters over a wide range of values. In general we use solar relative metal abundances (Grevesse et al. 2010) as a baseline. For Si we also include a higher value to reflect the observed range for Galactic metal-poor stars which, in a common pattern with other α -elements, extends from solar values to a substantial overabundance. For C, on the other hand, measurements for metal-poor stars generally give approximately the solar relative abundance, although with considerable scatter (Ryan et al. 1996; McWilliam 1997). A similar picture is gained from observations of cosmologically-distributed metal-poor DLA systems (Pettini et al. 2008; Pettini & Cooke 2012). However, overabundances comparable to metal-poor stars also occur at near-solar metallicities in Galactic stars (e.g., Pettini & Cooke 2012 and references therein). Based on all the above, we take $[\text{Si}/\text{C}] = 0.0, 0.4$ as representative “soft” limits and assume these values at all redshifts covered by our data. The other special case is N, which has quite a complex

from either of these sources at energies < 1 Ryd has insignificant effect on the ionic ratios we measure for the absorbers.

¹⁴In the usual fashion we express the logarithmic abundance of element X relative to element Y compared with the solar values as $[X/Y] = \log(X/Y) - \log(X/Y)_{\odot}$.

evolutionary nucleosynthetic origin (Henry et al. 2000; Henry & Prochaska 2007; Petitjean et al. 2008). In particular, the relative abundance of N in metal-poor DLA systems shows a downward scatter extending by about 1 dex within the primary and secondary production boundaries (Pettini et al. 2008; Pettini & Cooke 2012). We take $[\text{N}/\text{C}] = 0.0, -1.4$ as representative limits at all redshifts we cover.¹⁵

In Figure 17(b), first looking just at the data points, we show our specific *combinations* of the observed ionic column density ratios displayed in the top panel of Figure 16(a) and the panels of Figure 16(b) derived from the individual components in sample *sb*. Here in the first vertical set of panels we show Si IV/C IV : C II/C IV distributed over the three redshift intervals used in Figure 17(a). Again, the coded symbols indicate specific observational sub-sets of the data listed in Tables 2–10 and identified in the caption to Figure 16(a). In the three other vertical sets of panels in the figure, in similar fashion, we include N V/C IV, Si II/Si IV and Si II/C II as ratios with C II/C IV. It is particularly striking that the data here take on a more coherent appearance: values from components in a given system distributed vertically in Figures 16(a) and (b) now string out within a broad two-dimensional track, accomodating the different ionization states present. It is clear that such two-dimensional analyses help to make useful interpretations of the ionization properties of the absorbers.

To gain some initial insight into the cosmological drivers which influence the trend of our observations we begin by comparing our results with CLOUDY models confining the radiative input to the simple case of a metagalactic ionizing radiation background involving the Q_{HM} model alone, shown again in *dashed lines*. The two curves in

¹⁵However, we need to be cautious about the general interpretation of relative abundance values $[\text{Si}/\text{C}]$ and $[\text{N}/\text{C}]$ for the absorbers we observe. Given their apparent origin as ejecta from galaxies (Steidel et al. 2010) we should alternatively think of these as “beginning life” within galaxies at relatively high metallicities (e.g., Erb et al. 2006; Mannucci et al. 2009) and then becoming diluted in their subsequent transit into the immediate IGM (and making up part of the enriched circumgalactic medium (Adelberger et al. 2005b; Steidel et al. 2010): consequently, while the observed absorbers then indeed are of low metallicity, their relative metal abundances may not reflect a simple metal-poor environment.

each of the panels for Si IV/C IV : C II/C IV and Si II/C II : C II/C IV give our individual model results for the adopted bounding values combining $[\text{Si/C}] = 0.0, 0.4$ with the respective lower and higher redshifts in the range. In use here of our CLOUDY model curves we make small vertical adjustments specific to each of the sets involving Si IV/C IV, Si II/Si IV and Si II/C II, in magnitude averaging ~ 0.2 dex, to align with the relatively well-defined $1.9 < z < 2.6$ data (in practice we base this on the QG_{HM} model, given below, but closely similar values apply here to the Q_{HM} model), then propagate the same adjustments to the other two redshift intervals. This “calibrates” the assessment of the evolutionary trends from the lower to higher redshifts in our data. From this point, all the graphical results presented below use these same adjustments. We assume these small differences reflect the accuracy of values of atomic data and functional parameters employed in the code: earlier CLOUDY releases require different (still small) adjustments with the same data. We do not attempt this for N V/C IV because the range of the data and the possible range of the models do not give sufficient grounds for discerning similar small adjustments.

Still with just Q_{HM} , for Si IV/C IV : C II/C IV, in the lowest redshift interval ($1.9 < z < 2.6$) the two bounding curves fit our data quite well over much of the range. Progressing similarly to the higher redshifts, relative to the model results there is first an upward scatter in the data ($2.6 < z < 3.4$) then a collective rise by ~ 0.5 dex ($3.4 < z < 4.4$). Additionally, we note that at the higher redshifts there are relatively more components having C IV and Si IV but only upper limits for C II (the open symbols with arrows pointing out to low C II/C IV. Most of the components with only upper limits for both Si IV and C II have $N(\text{C IV}) \lesssim 5 \times 10^{12} \text{ cm}^{-2}$. We return to these factors in more detail in §9.

Next, for N V/C IV : C II/C IV, while our data here are rather sparse, a progressive evolutionary trend over the three redshift intervals is again indicated. With photoionization to N V requiring energies beyond 4 Ryd the presence at the highest redshifts of only upper limits for N V indicates a substantially softer spectral energy distribution for the ionizing flux than given by the initial model we show here, this pointing to the inclusion of

radiative contributions from galaxies as incorporated in the Haardt & Madau (2012) full radiative transfer computations we address below.

For Si II/Si IV : C II/C IV (here there is no relative abundance dependence), again in the first redshift interval the Q_{HM} model fits the data quite well, in the middle interval there is evidence for the beginning of a significant downward trend in the data, followed at the highest redshifts by a bulk shift down by ~ 0.6 dex from the model. Note here that these measurements require positive detection of Si IV as well as the baseline presence of C IV and this strongly restricts the range of upper limits relative to those appearing for Si IV/C IV : C II/C IV.

Finally, for Si II/C II : C II/C IV, the Q_{HM} model generally gives good fits to the data in the first two redshift intervals, while in the highest interval the data show a downward trend not well followed at the $z_{HM} = 3.4$ boundary in the model. Here the upper limits are restricted just to Si II by the need for positive detection of C II as well as C IV.

In summary of the above, while a radiation environment due only to QSO sources provides the basis for a reasonable match to the data in our lowest redshift interval, to higher redshifts the evident significant evolution in the data is not consistently reproduced, in particular for *the strong absorbers*, by this simple model.

We now include background radiation from both QSOs and galaxies (QG_{HM}) with their individual evolutionary behaviour, using the full Haardt & Madau (2012) development of the meta-galactic radiation environment. The CLOUDY-generated results based on these complete spectra are given, in *thick continuous lines*, alongside the Q_{HM} model in Figure 17(b).

For Si IV/C IV : C II/C IV, in the first redshift interval the dominance of QSOs makes the QG_{HM} and Q_{HM} model boundaries almost coincident; for the most part, both fit the data quite well. In the middle interval the two models remain close but the data show a significant departure from these models at the $z_{HM} = 3.4$ boundary. In the highest redshift interval, because of the positively evolving galaxy component and diminishing contribution from QSOs the evolutionary development of the Q_{HM} model becomes quite extensive and at

the $z_{HM} = 4.4$ boundary shows a substantial uplift relative to the Q_{HM} model, increasing strongly to the left along the C II/C IV axis, and here overall this model approaches a far more accommodating fit to the data than does the Q_{HM} model.

The picture here for N V/C IV : C II/C IV in the first and middle redshift intervals again is similar for the two models and they remain consistent with the data. In the highest redshift interval the QG_{HM} model at the $z_{HM} = 4.4$ boundary moves substantially down from the Q_{HM} model in consequence of the highly depressed continuum beyond the He II edge seen in Figure 17(a), and is consistent with the observational upper limits.

Unlike the other sets, for Si II/Si IV : C II/C IV the QG_{HM} and Q_{HM} model curves are almost identical in all the redshift intervals, but therefore still showing no tendency to follow the large downward progression of the data with redshift as already commented.

For Si II/C II : C II/C IV in the first two redshift intervals the two models are little different and both give good fits to the data. However, in the highest interval the $z_{HM} = 4.4$ boundary for the QG_{HM} model now lifts substantially away from both the Q_{HM} model and the data, while the relative downward trend in the data relative to the $z_{HM} = 3.4$ boundary remains.

Again summarizing, while the QG_{HM} metagalactic spectral energy distribution makes progress in meeting the observational data in the cases involving Si IV/C IV and N V/C IV, we cannot achieve simultaneously consistent fits to our full set of observed ionic ratio combinations over the complete redshift range *for the strong absorbers* with this model alone.

8.3. Effect of Delayed Reionization of Intergalactic He II?

Here we ask whether substantial further suppression of the metagalactic radiation intensity in the He II continuum can improve the fit to our high-redshift data. While in Haardt & Madau (2012) the discrete physical nature of absorbers is taken into account in the definition of “effective opacity” of the IGM, the discrete nature of the emitting sources is not. The radiative transfer formalism implicitly assumes a homogeneous *volume averaged* background intensity and yields

correspondingly homogeneous ionization properties of the IGM. This is a good assumption after He II reionization and the computed background intensity is appropriate for exposure of isolated absorbers. However, before full reionization of He II the IGM is highly inhomogeneous (e.g., Bolton et al. 2006; Shull et al. 2010), with expanding He III regions surrounding QSOs¹⁶ embedded in a medium limited to He II where at large there is little or no radiation beyond 54.4 eV. The ionization thresholds relating to the appearance and loss of Si IV and C IV (Si III: 33.5 eV; Si IV: 45.1 eV; C III: 47.9 eV; C IV: 64.5 eV) straddle the He II ionization edge and those of N IV and N V (respectively: 77.5 eV; 97.9 eV) lie well beyond, making the ionic balance of all these susceptible to such radiative inhomogeneities.

Alluding to this patchy nature of the reionization process Madau & Haardt (2009) pictured representative cases for the delayed reionization of He II by artificially increasing He II/H I in the IGM, with strong effect on the depth of absorption in the He II Lyman series and continuum of the background radiation. As we have already shown in §8.1 a significant demarcation around $z = 3$ is not indicated by the behaviour of Si IV/C IV median values as a function of redshift. However, now we are considering the more complete behaviour of several different combinations of ionic ratios containing one or both of Si IV and C IV. To get a gross idea of the possible effect on the radiation background of delayed reionization of He II we notionally follow Madau & Haardt (2009) beyond $z = 3$ (i.e., for our boundary values at $z_{HM} = 3.4$ and 4.4) but here for each value of $N(\text{H I})$ in the original model fix He II/H I and He I/H I at the value they have at $z \sim 6$.¹⁷ The spectral result is included, in *dotted lines*, in Figure 17(a). The He II continuum now is much deeper at $z_{HM} = 3.4$ than in the original case and also deeper at $z_{HM} = 4.4$ (but naturally to a lesser extent at this redshift because of the already existing incipient trend in this direction), while radiation over the rest of the spectra including at the He I ionization edge is not significantly affected. Then, interestingly, for $z_{HM} = 3.4$ and 4.4

¹⁶These “bubbles” have “fuzzy” boundaries due to the penetrating nature of the associated X-ray emission.

¹⁷Again, we are grateful for the provision of these additional results of the radiative transfer code (Haardt 2014).

the corresponding ionic ratio outcomes included in Figure 17(b) show significantly better concordance with the data for Si IV/C IV : C II/C IV, giving a necessary rise in the higher ionization region (i.e., to the left of the diagram), and remains consistent for N V/C IV : C II/C IV, (albeit within the assumed range of N/C relative abundance given in §8.2). However the outcome for Si II/C II : C II/C IV at $z_{HM} = 4.4$ relative to the data is considerably poorer than in the original and, most significantly, there is virtually no change for Si II/Si IV : C II/C IV. Taken all together, these results show that simple modifications in the He II opacity do not explain our high redshift data for the strong absorbers. To account for the expected cosmic variance arising from variously merging He III regions in the approach to full reionization we also try a combination of both the original and delayed reionization cases. Unsurprisingly this produces a result between the two and gets us no further.

In the following two sub-sections we continue with the QG_{HM} model to explore both the assumed validity of photoionization equilibrium as the dominant ionization process for the observed absorbers and the effects of changes in absorber parameters.

8.4. Photoionization Equilibrium or Collisional Ionization?

In pure collisional ionization equilibrium the C IV ionization fraction strongly peaks at 10^5 K (Sutherland & Dopita 1993) and there is a peak at about the same temperature in the more complicated case of a non-equilibrium radiatively cooling gas (Shapiro & Moore 1976; Tripp et al. 2002; Gnat & Steinberg 2007). Such a temperature corresponds to $b \simeq 10$ km s $^{-1}$ and is already ruled out for our narrower components (see the b -value distribution given in Figure 11(a)). In the same circumstances Si IV peaks at a slightly lower temperature: $\sim 0.8 \times 10^5$ K. In contrast, for photoionization equilibrium, CLOUDY modelling gives a mean temperature $\lesssim 0.5 \times 10^5$ K within the absorber gaseous column in the C II/C IV range of our data, as we show in the next sub-section.

To indicate the *additional* effects of collisional ionization, in Figure 18 (with downward extended axes) we show in *coded dashed lines* idealized model results from CLOUDY runs with our fiducial

absorber parameters at the two fixed temperatures $(1.0, 1.2) \times 10^5$ K in the presence of the model QG_{HM} ionizing background radiation and cosmic microwave background as before, contrasting the two intervals with bounding redshifts $z_{HM} = 1.9, 2.6$ and $3.4, 4.4$. In *continuous lines* we include for comparison displays of our four ionic ratio combinations obtained in pure photoionization equilibrium (PIE) with the model QG_{HM} as shown in Figure 17(b). The fixed temperature collisional ionization curves terminate in the diagrams where the ionic ratios become independent of total hydrogen volume density in the model. In the absence of ionizing radiation these models at all densities give single values at these termination points.

It is clear from the figure that at temperatures where collisional ionization would be dominant, these models, unlike the photoionization models at their equilibrium temperatures, bear little structural resemblance to our observations in Figure 17(b). We can conclude that the great majority of the absorbers in our samples are in or close to a state of photoionization equilibrium. It is important to note that in this there is *no significant distinction between the broader and narrower components* in the sample, which fit similarly well. This confirms that the broader components represent turbulent or bulk velocity-extended structures rather than regions at much higher temperature dominantly thermally broadened (see Fox et al. (2007b) for observations relating to DLA and sub-DLA systems).

8.5. Effect of Changes in Absorber Parameters?

In Figure 19 we demonstrate how the outputs of the four ionic ratio combinations we have used in Figure 17(b) for the QG_{HM} model are affected by changes in metallicity and H I column density and here again contrast the CLOUDY outputs for the low and high redshift intervals. The absorber fiducial case of $[Z] = -2.5$ and $N(\text{H I}) = 10^{15}$ cm $^{-2}$ is shown in *continuous lines*; the rest are coded as indicated. Corresponding displays for total hydrogen volume density, $n(\text{H})$, and mean temperature within the absorber gaseous column, $\langle T_e \rangle$, are included in the bottom two sets of panels.

In all cases shown, over the whole included C II/C IV range there is relatively little effect on

the computed results for the values $[Z] \lesssim -1.5$ and $N(\text{H I}) \lesssim 10^{16.0} \text{ cm}^{-2}$, while $\text{Si II}/\text{Si IV} : \text{C II}/\text{C IV}$ is almost invariant for all the listed parameter values. Comparison with the data in the corresponding panels of Figure 17(b) indicates that most of the strong, *detected*, components in our sample (i.e., those without upper limit values in their makeup) conform with these constraints. Even with a general extension to $[Z] \lesssim -1.0$ and $N(\text{H I}) \lesssim 10^{17.0} \text{ cm}^{-2}$, significant departures from the fiducial case occur only for $\log N(\text{C II})/N(\text{C IV}) \lesssim -0.5$. We note that to some extent such departures notionally can be included by our observational $\text{C II}/\text{C IV}$ upper limits in $\text{Si IV}/\text{C IV} : \text{C II}/\text{C IV}$.

Over the whole of the indicated parameter variations there is also comparatively little change in the $n(\text{H}) : \text{C II}/\text{C IV}$ relationship. For the *given radiation fields* in the QG_{HM} model $\text{C II}/\text{C IV}$ is thus a good indicator of the gas volume density of the absorbers. Using this, we see by comparison with at least the top two sets of panels in Figure 17(b) that the detected absorber components are there indicated to range in density over $n(\text{H}) \sim 10^{-3.5} - 10^{-2.5} \text{ cm}^{-3}$.

Concerning $\langle T_e \rangle$, for $\log N(\text{C II})/N(\text{C IV}) \lesssim -0.5$, raising $[Z]$ leads to a reduction in temperature (due to increased cooling). For the absorber components with Si and C b -values listed independently in Tables 2–10 (i.e., with $b(\text{Si})$ shown *unbracketted*: see §3 and §4) we obtain, following Rauch et al. (1996), an average absorber temperature of $(2.0 \pm 0.2) \times 10^4 \text{ K}$ over the range $-1.0 \lesssim \log N(\text{C II})/N(\text{C IV}) \lesssim 1.0$, broadly consistent with Figure 19. For $z < 3.1$ and $z > 3.1$ the respective values are $(1.9 \pm 0.3) \times 10^4 \text{ K}$ and $(2.1 \pm 0.4) \times 10^4 \text{ K}$, showing no significant change with redshift. These values are lower than the mean $3.8 \times 10^4 \text{ K}$ found by Rauch et al. (1996), but as we have explained in §3, on the one hand strictly we include here only the narrower components ($b \lesssim 10 \text{ km s}^{-1}$), and on the other, in their analysis, differential blending effects in broader components may give a tendency to estimate apparently higher temperatures.

An important conclusion from these results is that the systematic evolutionary effects exhibited in the ionic ratios are not caused simply by *changes in absorber properties*. We must therefore look to evolution in the *ionizing radiation environ-*

ment to explain the observations, as we develop next.

8.6. Template Galaxies Local to the Absorbers?

On the now general recognition discussed in §7 that absorbers such as in our sample are regions located in the outer extensions of galaxies (e.g., Steidel et al. 2010), we seek to account for our observations by augmenting the metagalactic background radiation with direct radiation from the star-forming regions within the local, *parent*, galaxy.

It should be noted that in computing the mean intensity of the *metagalactic* background radiation, all cosmologically distributed sources must be included from the outset. The results for additional such sources cannot just be added individually since the background radiation intensity determines the ionization balance of the clumpy intergalactic medium which in turn determines the character of the background radiation. However, in including the radiative effects of star-forming galaxies in the *local* environment of the absorbers, such contributions *can* be treated incrementally because we do not imply any addition of sources influencing the general background: in effect we are simply defining the *location of the absorbers* relative to the galaxies in the already existing population. Thus, a sufficiently isolated absorber will be exposed only to the metagalactic radiation while an absorber close to a galaxy will in addition experience a direct “proximity effect” within the ionizing spectral range 1–4 Ryd. For significant impact on our strong absorbers, from what we have found in §8.2, over much of this range the radiation from the local galaxy will need to *dominate* over the general background radiation.

Stars in galaxies at high redshift are born in dense protogalactic clumps with sufficient resident neutral hydrogen within the full galactic volumes to absorb most of the emitted ionizing radiation. That the IGM must be reionized by the action of such populations within $12 \lesssim z \lesssim 6$ and remain ionized thereafter gives demanding requirements for escape of a significant fraction of the stellar ionizing radiation from such highly attenuating environments (e.g., Bolton & Haehnelt 2007; Pawlik et al. 2009; Bouwens et al. 2012a; Haardt & Madau 2012; and see §8.2). While only very

small escape fractions are observed in galaxies at $z \lesssim 1$ (e.g., Leitherer et al. 1995; Siana et al. 2010) the needed increase with redshift is observationally indicated in some degree (e.g., Steidel et al. 2001; Giallongo et al. 2002; Shapley et al. 2006; Inoue et al. 2006; Iwata et al. 2009; Vanzella et al. 2010; Boutsia et al. 2011) albeit in an apparently patchy manner among galaxies at least as seen from our observational viewpoint. Simple model estimations of escape fraction (Dove & Shull 1994; Haiman & Loeb 1997; Madau et al. 1999; Dove et al. 2000; Ricotti & Shull 2000; Clarke & Oey 2002; Fujita et al. 2003; Fernandez & Shull 2011) as well as sophisticated simulations (e.g., Razoumov & Sommer-Larsen 2006, 2007, 2010; Gnedin et al. 2008; Wise & Cen 2009; Yajima et al. 2011; Smith et al. 2011; Kimm & Cen 2014) generally predict a wide range of values within the large uncertainties of the formulations for star formation, dust attenuation and supernova feedback, as discussed by many of the latter authors. Clarke & Oey (2002) and Fujita et al. (2003) propose specific effects of repeated supernova explosions to create galactic outflows which make “channels” enabling enhanced escape of ionizing radiation. Yajima et al. (2011) in their simulations find that the average escape fraction for galaxies at $z = 3\text{--}6$ steeply decreases as the halo mass increases because those with massive halos ($M_h \sim 10^{11} M_\odot$) have a densely clumpy gaseous structure enveloping the star-forming regions while with lower-mass halos ($M_h \sim 10^9 M_\odot$) conical regions of highly ionized gas often develop which allow the ionizing photons to escape, although with a large scatter in escape fraction. In common among such escape eventualities, high escape fractions require high “porosity” achieved only by very strong supernova feedback. Adelberger et al. (2003) stress the role of supernovae-driven superwinds in their observational study of the local gaseous environments of Lyman-break galaxies and the presence of C IV absorbers.

In relation to this we consider the possible influence on the balance of our ionic ratios of spectrally-dependent extinction by dust occurring in the local galaxies. In all quantitative studies of high redshift galaxies determination of reddening by dust leading to empirical extinction corrections throughout the (non-ionizing) far-ultraviolet to $\sim 1200 \text{ \AA}$ is common practice (e.g., Calzetti

et al. 1994, 2000; Seibert et al. 2002; Reddy et al. 2008, 2010; Bouwens et al. 2009, 2011, 2012b) but very little is known about the dust composition, grain size distribution and degree of sublimation (some amount of dust is likely to be destroyed by ionizing radiation) that would enable accurate extension into the H I Lyman continuum (e.g., Draine & Lee 1984; Martin & Rouleau 1990; Cruise 1993; Weingartner & Draine 2001; Binette et al. 2005). Broadly, the relevant extinction probably peaks near 800 \AA and diminishes thereafter (e.g., Pei 1992; Gnedin et al. 2008). However, in the prevailing environments we study here the *need* for accurate knowledge of extinction by dust over $1\text{--}4 \text{ Ryd}$ is rendered irrelevant if the ionizing radiation escapes only through channels sufficiently clear of absorption that there will be simply a *geometrical* attenuation not dependent on wavelength. With the spectral shape then preserved we may use a global escape fraction in this region, indeed following Haardt & Madau (2012) in their definition of $\langle f_{esc} \rangle$ for the metagalactic contribution (§8.2). It is interesting that even in the presence of additional “translucent” escape routes not “totally” cleared of significantly absorbing gas and dust the large effective absorption cross section of neutral hydrogen in this spectral region will override the effect of dust if the gas is not excessively ionized (the dust content relates to metallicity, therefore to total hydrogen, while the comparative weight of optical depths relates also to the residual neutral hydrogen). Gnedin et al. (2008) support such a picture in their full model simulations, finding the escape fraction at energies above 1 Ryd to be almost independent of dust absorption because the contribution from translucent points having included dust is small (see also Razoumov & Sommer-Larsen 2007). Thus hydrogen can be the dominant source of opacity in our range of interest above 1 Ryd while dust is the prime source below this. An obscuring hydrogen column density $N(\text{H I})$ greater than only a few $\times 10^{18} \text{ cm}^{-2}$ is sufficient to absorb essentially all the stellar ionizing radiation leaving the galaxy, while the constraint from γ -ray burst observations at $z \geq 2$ shows the value is generally much higher than this (Chen et al. 2007), so we shall assume in general that in this model any escape of ionizing radiation will come about through effective geometrical porosity alone.

Accordingly, for a local galaxy component we use an intrinsic spectral energy distribution similar to those applied as the distributed template galaxies in the Haardt & Madau (2012) QG_{HM} model, but now not modified by long passage through the IGM. For this we employ Starburst99 (Leitherer et al. 1999, 2010; we use the August 2010 release v6.0.2 throughout), which has ingredients close to the Bruzuel & Charlot (2003) GALAXEV models (Vázquez & Leitherer 2005). We model a galaxy of age 100 Myr undergoing continuous star formation, with Salpeter (1955) IMF over the mass range 0.1–100 M_{\odot} , using Geneva tracks with “high” mass-loss rates (these are optimized for young massive stars, of particular relevance here), and Pauldrach/Hillier atmospheres. For representative galaxy metallicities we are guided by the relation given by Haardt & Madau (2012), shown in §8.2, and take the closest options in Starburst99 of 0.4 solar at $z = 1.9$ and 2.6 and 0.2 solar at $z = 3.4$ and 4.4 (the implied differential effects in the modeling amount to $\sim 10\%$, small compared with the possible range in the galaxy mass-metallicity relation (e.g., Erb et al. 2006). We obtain low-resolution spectra (~ 20 Å) appropriate for input to the CLOUDY code.

To represent the ultraviolet luminosities of typical bright galaxies over our redshift range we take observed values for the characteristic absolute AB magnitude (Oke & Gunn 1983), M_{AB}^* , as follows: -20.7 ($z \sim 2$) and -21.0 ($z \sim 3$) at rest-frame 1700 Å from Reddy & Steidel (2009) and -21.0 ($z \sim 4$) and -20.6 ($z \sim 5$) at rest-frame 1600 Å from Bouwens et al. (2011). Interpolating over these we obtain at our boundary redshifts the respective values: -20.6 ($z \sim 1.9$), -20.9 ($z \sim 2.6$) and -21.0 ($z \sim 3.4$) at rest-frame 1700 Å and -20.9 ($z \sim 4.4$) at rest-frame 1600 Å. Over the same redshift range at these characteristic magnitudes dust extinction is relatively unchanging (Reddy et al. 2008; Bouwens et al. 2009):¹⁸ we use a representative extinction factor ~ 6 from Bouwens et al. (2009) to obtain the corresponding intrinsic (i.e., dust-corrected) values $M_{AB_{int}}^*$.¹⁹ Then, in line with our model assump-

tions discussed above, we use the values $M_{AB_{int}}^*$ at our adopted boundary redshifts to scale our Starburst99 model respectively at 1700 and 1600 Å to obtain the corresponding intrinsic spectral energy distribution extending through the H I Lyman continuum (the model intrinsic flux ratios at the H I Lyman limit relative to these wavelengths are respectively 0.39 and 0.36). Finally, to set appropriate 1–4 Ryd escape fractions at this stage, for consistency we apply the absolute values $\langle f_{esc} \rangle$ given by the Haardt & Madau (2012) formulation in §8.2: 0.0067 ($z = 1.9$); 0.014 ($z = 2.6$); 0.028 ($z = 3.4$); 0.056 ($z = 4.4$).²⁰ Translating the above, we obtain the following values for the *escaped* intrinsic 1 Ryd flux at 10 physical pc, $F_{\nu_{esc}}^*$ (912 Å) $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$: 9.9×10^{-14} ($z = 1.9$); 2.7×10^{-13} ($z = 2.6$); 5.9×10^{-13} ($z = 3.4$); 1.0×10^{-12} ($z = 4.4$).

Next, to set typical distances of prospective QSO absorbers from their parent galaxies we relate our relatively strong, complex absorbers in particular (i.e., those containing positively detected C IV, Si IV, C II and Si II) to the strong absorbers containing the same species Steidel et al. (2010) find from their direct observations of outflowing gas in the circumgalactic media (CGM) of relatively luminous star-forming (Lyman-break) galaxies at redshifts $2 \lesssim z \lesssim 3$ and which in character we extend here notionally to $z = 4.4$.²¹ They find strong *in-filling* circumgalactic absorption with an effective edge at a galactocentric radius ~ 80 physical kpc beyond which no metal ab-

luminosity in general show reduced extinction (Wang & Heckman 1996; Reddy et al. 2006; Reddy & Steidel 2009; Bouwens et al. 2009). Haardt & Madau (2012) in their derivation of the dust-reddened contribution of the *population* of galaxies to the metagalactic radiation background integrate well down the faint-end slope of the luminosity function and consequently apply the appropriate *luminosity-weighted extinction*. In the application we develop here we focus on the additional exposure experienced by an absorbing system in the close locality of a typical *individual* relatively bright galaxy (see below), therefore use a level of extinction consistent with the luminosity of the given galaxy we consider.

²⁰in §9 we develop the issue of escape fraction on the basis of quantitative results obtained from our further modeling.

²¹Steidel et al. (2010) use close angular pairs of galaxies of different redshifts, with the local environment of the nearer probed along the sightline to the further acting as source. This complementary technique vastly increases the sample size at these scales relative to the established method using QSOs.

¹⁸There is a strong redshift dependence beyond this, with extinction practically non-existent by $z \sim 7$ (Bouwens et al. 2012b).

¹⁹Additionally, at any redshift, due to correlation between star-formation rate and dust extinction, galaxies of lower

sorption is detected. Similar results are obtained by Adelberger et al. (2005b) at $1.8 \lesssim z \lesssim 3.3$ for C IV alone. Linking with this, we take such galaxies as typical objects in our computations.

Correspondingly, for the modeling in this section we use values 80 and 20 physical kpc as indicative galactocentric distances and add the resultant local spectral energy contributions at the absorbers, obtained from the flux values we have defined above, to the respective Haardt & Madau (2012) metagalactic ionizing background spectra at the z_{HM} boundaries.²² We then include the absorber values $[\text{Si}/\text{C}] = 0.0, 0.4$ as before to give the combined bounding values to proceed with the CLOUDY modeling.

In Figure 20(a), following the style of Figure 17(a), we give the corresponding spectral energy distributions in *continuous lines*, with the original Haardt & Madau QG_{HM} cases in *dashed lines* (here we no longer show the Q_{HM} model): both cases coincide above 4 Ryd because of the cut-off there in the galaxy spectrum. For reference, in *thick dotted lines* we also show the corresponding galactic spectra without application of an escape fraction. Moving to Figure 20(b), following the style of Figure 17(b), it is obvious that the shape of the galaxy full spectrum with attenuation invariant over 1–4 Ryd, as the current escape fraction provides, only achieves an evolving pattern that is, in the trend in redshift down the panels, manifestly a significantly *poorer* fit to the collective data for . In particular, at the highest redshifts: for Si IV/C IV : C II/C IV there is a significant drop in the right of the diagram; for Si II/Si IV : C II/C IV there is an overall rise still further from the data; and for Si II/C II : C II/C IV there is an increased large rise away from the data in the left half of the diagram. Again we stress that these conclusions apply in particular to the *strong absorbers* having positive detections for all species within each set of ionic ratios we display (we consider the partial upper limit cases later). These model results are not critically sensitive to the distance of the absorber: for these three sets we find no significant changes when we vary the received intensity at the absorber by placement

at galactocentric radii anywhere from closer in to positions widely spaced between the two adopted values. Evidently this is because the galaxy spectrum strongly dominates over the ultraviolet background spectrum in the whole range 1–4 Ryd and no effective change in spectral *shape* occurs within wide exposure limits. There is less to comment about N V/C IV : C II/C IV other than the lack of galactic radiation in the He II ionization continuum reduces the computed values further in the direction below the observed upper limits, similarly to that shown in Figure 17(b), and which here for $z_{HM} = 4.4$ takes it below the bottom of the diagram.

To explain the poor fits pervading Figure 20(b), as possible cause, the synthesized galaxy models that are assumed inevitably must be a relatively loose approximation in the description of the emergent ionizing flux at energies above 1 Ryd because of the uncertainties in modeling the properties of the hot star population, both in definition of evolutionary tracks and in treatment of atmospheres (Stasińska & Schaerer 1997; Crowther 2000; Kewley et al. 2001; Pauldrach et al. 2001; Smith et al. 2002; Vázquez et al. 2007; Simón-Díaz & Stasińska 2008; Eldridge & Stanway 2009; Levesque et al. 2012), and while synthesis models are available which give somewhat more emphasis to the hot star population (e.g., Fioc & Rocca-Volmerange 1997; Leitherer et al. 1999; Smith et al. 2002) the lack of feasible corroborating observations at the short wavelengths of interest here compounds the uncertainty. Moreover, the star-formation rate is likely to be varying (Bruzual & Charlot 2003; Leitherer et al. 1999; Kolatt et al. 1999) and because of the short lives of massive stars such variation is greatly amplified in the ionizing far ultraviolet and, to maintain a high average luminosity, the duty cycle needs to be appropriately high: thus, while a constant star formation rate may be a good approximation at the longer wavelengths this might be too simplistic for what is required here.

However, the *required* spectral change is greater than implied by such possible modeling deficiencies. We find in practice that we can readily adjust the stellar IMF to give changes in the resultant population-synthesised galaxy spectra that enable the CLOUDY-generated outcomes indeed to become reasonable fits to the data. Essentially this

²²We continue with the designations z_{HM} in the figures because in all cases including those with additional local sources we “ride” on the Haardt & Madau (2012) metagalactic ionizing background.

simply means truncating the IMF at a maximum near $20 M_{\odot}$ to remove the contributions from all the hottest stars. But this will not be a physically sound solution. Galaxy spectra observed at high redshifts in the rest-frame far-ultraviolet below 1 Ryd (where the parent galaxy is transparent, albeit with attenuation by dust) are seen to be dominated by emission from O and B stars. In particular, the common presence of the P Cygni profiles of the N v and C iv resonance lines demonstrates the existence of short-lived very hot stars near the top of the stellar mass range. These galaxy spectra are best matched by regions undergoing continuous star formation with stellar populations having a Salpeter IMF showing no evidence for deficiency of the most massive stars (e.g., Pettini et al. 2000; Shapley et al. 2003; Steidel et al. 2003; Erb et al. 2010). The inclusion of this full range of stellar masses must therefore be a *condition* of any star-forming model we adopt.

To test whether the solution is simply to introduce some partial attenuation by H I we include an absorbing region having $N(\text{H I}) = 10^{18} \text{ cm}^{-2}$ between the emitted galaxy spectrum and the CGM absorbers at $z_{HM} = 4.4$ and in Figure 20(a) show the spectral result in *fine dotted line* and reflecting the shape of the H I photoionization cross-section which peaks at 1 Ryd and steeply falls to a small value by 4 Ryd). However, overall, the corresponding CLOUDY results in Figure 20(b) become yet further removed from coming to a match with the data compared.

As an alternative to continuous star-formation it might be argued that the answer lies in the functioning of *instantaneous* starbursts having the necessary full range of initial stellar masses. With delay of a few Myr after onset, when the hottest stars have exploded but those hot enough to produce substantial ionizing radiation still remain, the collective spectral content could provide the needed match. This is indeed so. But here the effective age-band to yield the observed ionic characteristics of the absorbers is itself only a few Myr: for a given isolated pairing of a specific star-forming region and a nearby absorber observed along a QSO sightline this means an unlikely fine-tuning. Regardless of this, reliance on such a one-to-one relation is not plausible because the galaxy as a whole has to appear spectrally complete in the observable far-ultraviolet at energies below 1 Ryd and

this means essentially continuous star-formation when integrated over all regions in the galaxy, which then brings the situation at the absorber back to square one.

We conclude that the highly significant mismatch between the collection of observed ionic ratio combinations of the strong absorbers and the model predictions relating to the region above 1 Ryd reveals that purely geometrical leakage of the ionizing radiation through absorptively-clear channels is *physically* an incomplete representation.

Changing direction, we show next that a dynamically-dependent stellar scenario well enables a robust match to our data requirements while still in the full spectral domain of the population synthesis model with continuous star formation that we use above.

9. SPECTRALLY MODIFIED IONIZING RADIATION FROM TEMPLATE GALAXIES BY ESCAPE OF RUN-AWAY STARS

It is well known that a significant fraction of massive stars in the Galaxy are moving with higher than usual velocities ($\gtrsim 30 \text{ km s}^{-1}$). Two processes are proposed for the origin of these “run-away stars”: dynamical ejection from dense young stellar systems soon after their birth (e.g., Poveda et al. 1967; Gies & Bolton 1986) and delayed ejection by explosion of a companion star (e.g., Blaauw 1961; Stone 1991). Which scenario dominates remains uncertain (e.g., Poveda et al. 1967; Hoogerwerf et al. 2001; Tetzlaff et al. 2011). From a catalogue of young (up to $\sim 50 \text{ Myr}$) runaway Hipparcos stars within 3 kpc of the Sun Tetzlaff et al. (2011) indicate for these a runaway frequency $\sim 30\%$ and the same kinematic properties no matter whether of low or high mass within the observed range.²³ They present a peculiar velocity distribution peaking at $\sim 35 \text{ km s}^{-1}$ and tailing to $\sim 100 \text{ km s}^{-1}$, which we show in the top panel

²³Following Tetzlaff et al. (2011) we do not include differential weighting to address possible tendencies for mass-related rates of ejection of runaway stars (e.g., Anosova 1986; Gies & Bolton 1986; Stone 1991). Nevertheless, as becomes clear in the development below, such aspects can have little effect on our results because of the overriding influence of the mass-selective runaway process in the application here.

of Figure 22; however, they do not apportionate between the two scenarios. As was first noted by Dove & Shull (1994) and later advanced by Conroy & Kratter (2012) using a simplified analytic treatment, the high speeds of runaway stars enable a useful proportion of the wide range of massive stars, i.e., those radiating strongly in the ionizing spectral region, to travel out of their dense environments of origin and through the surrounding highly absorbing gaseous envelope before they explode at the end of their several Myr and upwards lifetimes. Thus, the supernova feedback facilitated “passive” escape of internal ionizing radiation into the CGM and IGM through transparent channels, addressed in §8.6, is transposed into the initial *kinematic* escape of the ionizing *sources* themselves. This process becomes more efficient at high redshifts when galaxies are much smaller than locally in the Universe (Bouwens et al. 2004; Pérez-González et al. 2008; Oesch et al. 2010; Ono et al. 2013). Conroy & Kratter (2012) show that the radiation from runaway stars that have migrated to the low-density outer regions of high-redshift galaxies can be the dominant contributors to the reionization of the Universe. They also find that runaways ejected through dynamical encounters are far more effective than by the supernova explosion of a close companion because the delay of the latter event means very significantly shorter runaway-active lifetimes for the more massive of the ejectees. However, Kimm & Cen (2014) find from detailed high-resolution cosmological radiation hydrodynamics simulations that inclusion of runaway OB stars increases only mildly the mean escape fraction of H I ionizing radiation over that from their new supernova feedback model which has higher yield than the non-runaway counterpart of Conroy & Kratter (2012). Both studies deal with models aimed at the period of reionization for $z \gtrsim 7$ while this paper relates to our observed range $z = 1.9\text{--}4.4$ with *ongoing* ionization and involving somewhat more developed galactic structures.

In our new modeling below we develop the runaway concept considerably further by formally adding the resulting *spectral* changes that are induced in the final efflux of radiation. In this we consider both the dynamical ejection and supernova ejection mechanisms. Depending on the placing of a given star-forming region within the

dense gaseous envelope of a galaxy and the velocity distribution of runaway stars, the most massive runaway stars, having the shortest main sequence lifetimes, may not escape at all from the effective boundary of galactic absorption before their demise, while to lower masses there will be an age threshold for escape after formation when longer-living stars can spend a good fraction of their main sequence lifetimes in adequately clear space. In effect, for given physical parameters, this introduces specific limits on the maximum *active* stellar mass, only from below which can ionizing radiation be received. Then progressively to lower masses the corresponding radiative contributions both increase in time-span and are moderated by attendant intrinsic diminution in emitted flux coupled with substantial spectral softening: we show a range of indicative examples in the top panel of Figure 21 (explained in more detail in the following sub-section). In aggregate this results in a large modification of the emergent ionizing spectrum due to runaway stars to one much attenuated at the higher energies approaching 4 Ryd while remaining considerably less affected at 1 Ryd where the H I ionizing radiation is most effective and is generally accounted quantitatively (the H I photoionization cross-section drops steeply from 1 Ryd to higher energies). As already indicated in §8.6, we find such changes are the key requirement for coming to convergence with our observations.

We stress that in this modeling we do not compromise our underlying requirement for enabling the full intrinsic spectral characterization of the synthesized high-redshift galaxy spectra in the non-ionizing far-ultraviolet range. All stars in a continuous formation process extending over the full mass range are present here identically as in the model in §8.6 and the galaxy would appear the same spectrally in the observationally transparent range (taking due account of internal attenuation by dust). The difference occurs in the practically unobservable spectral region at energies above 1 Ryd, where our kinematic modification enters in a systematic manner to overcome the gaseous obscuration for stars that escape from it but leaves blocked the contribution of stars that do not make it out before terminating. In contrast, the porosity model needs to provide sightlines along channels transparent to ionizing radiation extending from stars in their original siting, so revealing the full

spectral content in the ionizing region; but as we show in §8.6 the indications from the ionic ratios we observe for our strong absorbers count against such clear paths at least in these cases. Moreover, as we also show, if at any point along the channel sightline there remains significant gaseous attenuation, the shape of the H I photoionization cross-section gives a resultant spectral distribution depressed at the lower energies in the range 1–4 Ryd which, as we see from the bottom panel of Figure 20(a) and the top panel of Figure 21, is modified in the “wrong” direction.

Using simplified galactic structures we now proceed in an *empirical* approach to explore the resultant implications leading from the runaway scenario to produce the spectral outcomes that through our CLOUDY modeling give a good match to our evolving observational results and in particular for the strong absorbers. We include related indications of the effect of the gravitational potential due to galaxy and halo mass on the motion of the runaways.

9.1. Method

9.1.1. Spectral Modeling

We model the runaway-modified 1–4 Ryd spectral emission from galaxies in continuous star-formation by use of Starburst99 with the same overall parameters as applied in §8.6 (including both applicable metallicities 0.4 and 0.2 Z_{\odot} to accommodate our redshift range) but since the radiative product of the runaway process is dependent on stellar mass as well as galaxy geometry we apply the following set of procedures while still encompassing the full mass range 0.1–100 M_{\odot} .

(i) For both of the two metallicities we segment the full mass range into narrow component slices (we use 2 M_{\odot}) within the overlying Salpeter IMF, then with Starburst99 compute with parameters as in §8.6 two sets of fifty individually-derived component spectra pertaining to the specific mass intervals of the slices, and in this way collectively cover the whole mass range as before. In the top panel of Figure 21 we show a selection of these individual component spectra which indicate the significant changes with mass that underly our approach. In particular we point to the strongly developing He I ionization edge from $\sim 25 M_{\odot}$ to lower masses.

(ii) Next, for each of the component mass slices from (i) we obtain the mass-dependent fraction of main-sequence lifetime remaining after each of an empirical set of trial *potential* escape intervals. In dynamical ejection we take the time from formation of an individual star to its departure from the effective boundary of galactic absorption. In supernova ejection we include an appropriate precursor interval, taking 4 Myr as a reasonable trial indicator (with increasing interval there is rapidly diminishing residual ionizing radiation). For main sequence lifetimes we use the formulation given by Hurley et al. (2000), again at metallicities 0.4 and 0.2 Z_{\odot} (however, within this interval the change in model lifetime with metallicity is slight). In the second panel of Figure 21 we show this function of stellar mass (at the average 0.3 Z_{\odot}) and in the third give illustrative examples of tracks of fractional active lifetimes for a range of trial escape intervals. The relatively shallow trend of main sequence lifetimes extending over the higher mass range, with the resultant confinement of escapees to lower masses after intervals exceeding ~ 4 Myr coupled with coincident development of the He I ionization edge, provides the progressive spectral consequences heralded by the composite ionic data we observe in the strong absorbers over our redshift range.

(iii) Continuing from (ii), from the view of the *circumgalactic absorbers*, at whatever point a star appears from the boundary of the absorptive confines of its galaxy it will illuminate the whole available hemisphere and therefore be widely accessible to a given absorber without critical placing other than being on that side of the galaxy. For putative simple galaxy structures we assume star formation occurs largely in a compact stellar core in spheroidals and closely confined to the central plane in disks. We indicate such geometrical constructs as idealized cartoons in the bottom panel of Figure 21. In spheroidal models, escaping stars of a given velocity individually will reach the absorptive boundary of the galaxy after the same time interval from initiation. As these appear, a relatively distant absorber will receive ionizing radiation from sites only at the boundary of the hemisphere in its direct view. However, depending on remaining main sequence lifetime, as stars continue to move outward in their paths, those exiting from parts of the surface hidden to the

absorber will rise above the boundary horizon and can add significantly to the illumination of the absorber. We illustrate this after an interval $P_{v,t}$ defining stars of given velocity and time after initiation: in this example those in the large portion of the spherical surface shown in *dashed line* illuminate the absorber while those in the small region shown in *continuous line* are obscured by the galaxy. Such obscuration relates only to the radius of the absorptive boundary of the galaxy (we show this region shaded by vertical *dotted lines*), so the larger is $P_{v,t}$ the rapidly greater is the illuminating fraction (i.e., the fractional surface area of the *dashed line* cap relative to the surface area of the underlying whole sphere). Conversely, for disks the body of the galaxy continues to obscure the stars departing from the far side. Furthermore, the internal stellar trajectories are more varied, with stars originating from a specific region in the plane reaching the absorptive boundary after transit times resulting from a wide range of slant distances. We show one such transit with the same interval $P_{v,t}$ and corresponding spherical surface similarly coded and here it can be seen that the resulting illuminating fraction is much smaller. Thus in similar circumstances stars in disk-like galaxies proceed out of the confining gas with intrinsically lower geometrical efficiency than in spheroidals. Nevertheless, disks naturally present thinner gas layers to be overcome than spheroidals and this enables more massive, therefore more luminous, stars to escape within their lifetimes. Together, these two forms give due scope for the evolution in spectral outcomes our observations indicate.

(iv) For both the spheroidal and disk structures we include the fractional main sequence lifetimes within each of the set of trial escape intervals in (ii) together with the corresponding illuminating fractions in (iii) to scale the associated component spectra in (i) for each defined escape interval then sum all individual products to obtain the total spectral outcome for each interval. We find that a set of trial escape intervals covering the range 2–15 Myr for dynamical ejection and a time-shifted set covering 6–15 Myr for supernova ejection are sufficient for application in the further procedures here described.

(v) Now to relate these trial escape *intervals* to a set of trial escape *distances* within a galaxy from

the site of star-formation to the effective boundary of absorption, we use the velocity distribution of the population of runaway stars (Tetzlaff et al. 2011) given in the top panel of Figure 22 and for each of the trial escape intervals scale the integral spectral outcome obtained in (iv) by the relative weighting of the specific stellar velocity linking each escape interval with each trial escape distance defined. Then for each of such *distance-based* composite sets we sum all the related velocity-based ($\gtrsim 30 \text{ km}^{-1}$) spectral products to obtain the corresponding total spectral contribution, and scale each relative to the whole stellar population by 0.3 to account for the fraction of runaway stars (Tetzlaff et al. 2011). For each model case we define the escape fraction relevant at the absorber, which here we term $f_{esc-abs}$, by the ratio at 1 Ryd of the received computed flux to the possible intrinsic flux from the same star-forming site in the galaxy but without attenuation or other modification, obtained from the summation of the basic component spectra in (i).

(vi) Recognising the far greater effectiveness of dynamical ejection over supernova ejection (Conroy & Kratter (2012); and as we find in our work below), but that the balance between these scenarios is uncertain, in the computations that follow we take each case separately for quantitative comparison.

(vii) To complete the spectra by extending to the observable non-ionizing region at energies below 1 Ryd we use the same unmodified, dust-extinction-corrected spectra as in §8.6. Finally, at this stage, across the redshift range we add, as explained in §8.6, the Haardt & Madau (2012) metagalactic flux QG_{HM} to the local galaxy spectral contributions before CLOUDY modeling. With these we make iterative trials of boundary escape distances for both the galaxy structures, comparing the generated CLOUDY values of ionic ratio combinations with the values from our observations for each adopted redshift interval. We find evolving escape distances in the range 100–600 pc most useful in associating the resultant spectral outcomes with our data, as we explain more fully in §9.2.

9.1.2. Gravitational Modeling

Additionally, we assess the possible dynamical consequences to the runaway stars from the grav-

itational potentials relating to their parent galaxies.

While pure dark matter simulations produce a consistent picture of the formation and evolution of large-scale structure in the Λ CDM cosmology (e.g., Navarro et al. 1997), far more detailed simulations are needed to describe the combination of dark matter and baryonic matter distributions within the scale of single galaxies. Zemp et al. (2011) in a structural study of galaxies at $z = 2-4$ using cosmological simulations which include modeling of the interstellar medium and star formation show the matter distribution as individual radial profiles for the star, gas and dark matter components. Within the overall baryon to dark matter universal mass fraction for the system (reached in aggregate at the outskirts of the halo) there is large radial variation among these components, with a strong concentration to a dominant baryonic core and a halo which is very markedly depressed generally within a few kpc of the centre. We reflect such mass distributions in our simple analytical density models below. While we always include such halos in our models, within our redshift range we concern ourselves only with escape beyond the gaseous boundary of a galaxy not from its dark-matter halo, and find that our runaway stars are influenced predominantly by the baryonic mass distributions with halo mass having relatively minor effect on the trajectories.

To represent our spheroidal galaxy model we use Plummer's (1911) simple approximation for the radial mass density distribution function given by

$$\rho(r) = \frac{3b^2M}{4\pi} \frac{1}{[r^2 + b^2]^{5/2}}, \quad (8)$$

where b is the radial softening length. For disk-like structures, we use the Miyamoto & Nagai (1975) three-dimensional model which in cylindrical coordinates (r, z) is given by

$$\rho(r, z) = \frac{b^2M}{4\pi} \frac{ar^2 + [(a + 3(z^2 + b^2)^{1/2})[a + (z^2 + b^2)^{1/2}]^2]}{[r^2 + (a + (z^2 + b^2)^{1/2})^2]^{5/2} (z^2 + b^2)^{3/2}}, \quad (9)$$

where a and b are axial softening lengths, and reducing to the Plummer model when $a = z = 0$.

In both cases we approximate their dark matter halos by a spheroidal form (Zemp et al. 2011) using Plummer distributions with radial softening length 2–3 kpc according to halo mass, and make the baryon content 0.17 of halo mass (Komatsu et al. 2011). The paths of test particles in the relevant gravitational potentials are computed by integration using the fourth-order Hermite method (Makino & Aarseth 1992). In the middle and bottom panels of Figure 22 we show trajectories in a selection of indicative cases for particles originating with velocities 30, 50 and 70 km s⁻¹ moving radially from the core of spheroids and vertically from the plane of disks. We make this restriction in the latter case to avoid crowding in the figure; however in our spectral modeling above we include ejection fully into spherical space from any point in the plane of the disk, as we indicate in the cartoon in Figure 21. Depending on its mass a given star will terminate in its trajectory at the end of its main sequence lifetime. If initiated dynamically shortly after its formation, in Figure 22 this can be referred to the abscissa: along this axis in the bottom panel (but applying equally to the middle panel) we mark some examples of such end points with indicated masses. For delayed supernova ejection the masses at the marked end points are correspondingly lower.

The figure shows that for spheroidal forms the stellar trajectories at velocities $\gtrsim 30$ km s⁻¹ are relatively little influenced at halo mass 10^8 and $10^9 M_\odot$ while stars remain strongly contained from $\sim 10^{10} M_\odot$. However for disk-like forms at halo mass $\sim 10^{10} M_\odot$ the trajectories still allow substantial periods outside the galaxy, and if they have sufficient remaining lifetime can return, pass through the obscuring confines of the galaxy and out again on the other side. While from the point of view of the absorber such oscillating paths include the prospect of reappearing on the near side after passage back again through the galaxy, this loses some advantage by significant expenditure of lifetime. For contribution to the metagalactic radiation background (see §9.2.2) stars are available from wherever they emerge from the galaxy. Such re-entrant transits also apply to the spheroidal case but the different geometry scales make this ineffective for the relatively short-lived stars applicable here.

Having indicated the range of feasibility for es-

cape of runaway stars from the simple galactic structures considered here we go no further in engaging such outcomes in detail in our spectral modeling in §9.2 following. In a simplified trial, however, we find that in suppressing the low end of the velocity distribution, at which escape is more difficult (Figure 22), only minor spectral changes are induced. This is due largely to the relatively small intrinsic radiative contribution by stars escaping with low velocity which selectively are biased to lower mass.

At much higher redshifts Conroy & Kratter (2012) consider a halo mass range $10^7 - 10^{10} M_\odot$ and find that their runaway stars effectually peak in radiative output relative to the non-runaway population at $\sim 3 \times 10^8 M_\odot$ (the effect of the potential due to the galaxy and halo mass on the motion of the runaways is considered negligible).

9.2. Results

9.2.1. Ionizing Radiation at the Local Absorbers

Following the pattern of Figure 20(a), we show in Figure 23(a) an empirically derived set of our new spectra obtained from the computations defined in §9.1.1 and containing physical parameters identified below. For reference we include in *dashed lines* the displays of the metagalactic ionizing radiation background alone (QG_{HM}) and in *fine dotted lines* these combined with full intrinsic galaxy spectra selected from Figure 20(a) with the adopted nominal escape fractions referred at 1 Ryd and received at the galactic distance 20 physical kpc ($QG_{HM}+G_{FULL}$). However, the new spectral results we now present contain the *derived* runaway-generated escape fractions pertaining at the local absorbers, $f_{esc-run}$, not these nominal values. Therefore to assist visual comparison with the intrinsic spectral shapes from Figure 20(a) we normalize the runaway spectra at 1 Ryd by making corresponding adjustments of the galactic distance for these. For the dynamical ejection case shown in *continuous lines* we do this directly while maintaining the outer limit at 80 physical kpc. For the supernova ejection counterpart, in *bold dotted lines*, we use the same derived distances as a simple means of relative comparison of both ejection outcomes. All such resultant distances (identified in the figure) come within the observed range for the circumgalactic absorbers defined by Steidel et

al. (2010).

Evidently there is a clear evolutionary trend with increasing redshift, showing development of a deep He I ionization discontinuity together with diminishing spectral intensity to higher energies characteristic of stars having mass from around $25 M_\odot$ to lower values as indicated in Figure 21, contrasting with the corresponding $QG_{HM}+G_{FULL}$ cases. The He I discontinuity has a marked effect on the lower ionization species of C and Si and for the strong absorbers at our highest redshifts is the dominant feature providing the necessary changes to bring together the predicted and observed ionic ratios.²⁴ Within this trend, at $z_{HM} = 1.9$ and 2.6 we do find the need for significant contributions from the more massive stars, but with the concomitant requirement for much smaller escape fractions for galactic ionizing radiation than at the higher redshifts as formalized in equation (7). Nevertheless, the full intrinsic spectrum still has too much emphasis at the higher energies and the modified runaway contribution gives a significantly better fit than seen in the panels of Figure 20(b). Any “toleration” for the presence of the hotter stars disappears by $z_{HM} = 3.4$ and continues to our observational boundary at $z_{HM} = 4.4$. We discuss the underlying physical consequences of these spectra more fully in association with the related ionization results which follow below.

But first there is need for some important clarifying remarks. Foremost, as we have already highlighted in §8.6 and indicate again above, we take it that our data containing solid measurements of all the species C IV, C II, Si IV and Si II relate directly to the observational regime in Steidel et al. (2010), namely *strong absorbers within circumgalactic media associated with relatively luminous galaxies*. We have in addition numerous partial and full upper limits which we must expect represent weak absorbers present in a continuum of corresponding environments presumably including regions around more compact galaxies, especially at our higher redshifts, as well as extending beyond the CGM nominal perimeter at any redshift. We address this in §9.2.2 in consideration of the

²⁴The ionization potentials of C II and He I, respectively 24.376 eV and 24.581 eV, nearly coincide, with the consequence of enhancing the ionization of Si II relative to C II and Si IV thus preferentially reducing Si II/Si IV and Si II/C II.

collective contributions to *metagalactic* radiation. Second, while the *location* of a strong absorber relative to its parent galaxy is arbitrary for the QSO sightlines that we probe, and can be regarded as a natural degree of freedom, the ionic results we obtain here give information on the *specific spectral shape* of the ionizing radiation received from the *specific galaxy* and our data enable us to identify this shape which in turn gives evidence on the geometry of the galaxy. Here we deduce indicative “absorptive boundary” cases which spectrally achieve a good matching *envelope* to our observational distributions within each displayed redshift interval. While these necessarily demonstrate feasibility, they represent only a part of the population and generally not the most *emissive* examples within the given redshift interval.

Now to Figure 23(b). Following the layout of the panels in Figure 20(b), we show the resulting CLOUDY predictions for the applied spectra presented in Figure 23(a) (these spectra represent the *conclusions* of the iterative procedure explained in §9.1.1 which yields the results shown here) and computed for the same fiducial absorber parameters defined earlier. As usual, to avoid overcrowding in the displays we combine the physical absorber distances with the values $[\text{Si}/\text{C}] = 0.0, 0.4$ to give extreme bounding values for the modeling displayed within each redshift interval, but it should be visualized that both these relative abundance values (and values between) associate with *each* individual redshift. Taking all redshift intervals together, these new models give good fits to the data, contrasting strongly with the set of non-runaway nominal full spectrum cases in Figure 20(b). Information on this set of results now follows.

In the top panels ($1.9 < z < 2.6$) we show runaway results for a disk model with dense H I boundary of semi-height 200 pc (D200) for both redshifts. As experienced by an individual circumgalactic absorber, the value of $f_{\text{esc-run}}$ for *dynamical* ejection that we derive for this (assuming this is the sole contributor) is 0.020, larger than the respective values 0.014 and 0.0067 at $z_{\text{HM}} = 2.6$ and 1.9 given by equation (7). As indicated in Figure 23(a), to normalize the 1 Ryd spectral flux at $z_{\text{HM}} = 2.6$ to that in Figure 20(a), here we make the corresponding absorber distance 24 kpc while at $z_{\text{HM}} = 1.9$ leaving 80 kpc as the CGM

effective perimeter. Good fits are obtained in all four ionic ratio combinations in this redshift interval. For the associated *supernova* ejected case at $z_{\text{HM}} = 1.9$ and 2.6 (again assuming this is the sole contributor) we obtain $f_{\text{esc-run}} = 0.0015$, about 7 percent of the dynamically ejected value and giving results in the first and fourth panels which by themselves are poor fits to the data but can be accommodated if these are a contribution together with dynamical ejection. Notwithstanding its existence we conclude that supernova ejection is a negligible contributor to the emitted ionizing radiation in this redshift interval, in agreement with the findings by Conroy & Kratzer (2012). However, if such stars are part of the population of directly observed runaway stars (Tetzlaff et al. 2011) this needs to be accounted within the nominal 30% total. On arbitrary supposition that both mechanisms are represented in equal numbers the total becomes $f_{\text{esc-run}} = 0.011$ (i.e., $(0.020+0.0015)/2$). A spheroidal model of boundary radius 200 pc (S200) fits equally well to the data, as we show in the figure for the example of dynamical ejection at $z_{\text{HM}} = 2.6$. For this model we obtain $f_{\text{esc-run}} = 0.096$ and corresponding absorber distance 53 kpc for solely dynamical ejection and $f_{\text{esc-run}} = 0.052$ if both mechanisms are there in equal numbers. While such a compact structure, by itself, may not be as plausible as a thin disk model, it may well represent component regions within extended lumpy structures such as are observed in this redshift range (e.g., Papovich et al. 2005; Law et al. 2007, 2012).

In the middle panels ($2.6 < z < 3.4$) we use the same D200 model at $z_{\text{HM}} = 2.6$ and 80 kpc, and at $z_{\text{HM}} = 3.4$ show results for a spheroidal model of boundary radius 400 pc (S400). For dynamical ejection good fits to the data are obtained across the four panels in this redshift interval; if this is the sole contributor S400 gives $f_{\text{esc-run}} = 0.020$, comparable with the value 0.028 from equation (7), and to normalize the flux at the absorber to that in Figure 20, the corresponding absorber distance is 17 kpc. For supernova ejection, if alone, we obtain $f_{\text{esc-run}} = 0.0042$, about 20 percent of the dynamical ejection value and giving CLOUDY results which again can be accommodated within the data (indeed quite helpfully in the fourth panel) but, again, only as a minor contributor together with dynamical ejection. As before, if both mech-

anisms exist in equal numbers, $f_{esc-run} = 0.012$. A spheroidal model at $z_{HM} = 3.4$ with boundary radius 300 pc (S300), gives results still fitting the data quite well for dynamical ejection, and if the sole contributor we obtain $f_{esc-run} = 0.035$ with corresponding absorber distance 23 kpc. If both mechanisms are represented in equal numbers, $f_{esc-run} = 0.021$. The spheroidal model S200 at $z_{HM} = 3.4$ gives much poorer fits to the strong absorbers across all panels here.

In the bottom panels ($3.4 < z < 4.4$) we use the same S400 spheroidal model for $z_{HM} = 3.4$ now at boundary radius 80 kpc and for $z_{HM} = 4.4$ have a model with boundary radius 600 pc (S600) giving $f_{esc-run} = 0.0068$ for solely dynamical ejection, much lower than the value 0.056 from equation (7). The corresponding normalizing absorber distance is 7 kpc. However, good fits are obtained throughout the four panels. The resultant particular outcomes in this defining redshift range are: Si IV/C IV : C II/C IV now lifts to accommodate the data and extensive upper limits; Si II/Si IV : C II/C IV shows the necessary substantial downward shift; Si II/C II : C II/C IV fits closely on the data; and N V/C IV : C II/C IV remains consistent with the data. In addition, at the closer galactic distance now applying at $z_{HM} = 4.4$ we indicate the effect of raising the metallicity of the model absorbers from the fiducial level $[Z] = -2.5$ to -1.3 , and is useful especially for Si II/Si IV : C II/C IV. As touched on in §8.2, this can illustrate a relatively early stage in the presumed progressive dilution of the outflowing galactic material as it merges with the rest of the CGM in its transit. Back to the nominal $[Z] = -2.5$, for the associated supernova ejected case we obtain $f_{esc-run} = 0.0013$, again about 20 percent of the dynamically ejected value, therefore still a minor contributor, but here giving results at $z_{HM} = 4.4$ in the panels which well fit within the data. Clearly this is because dynamical ejection here already has inherent long transit times due to the relatively long physical pathlengths required for the fits to the data at our high redshifts. Thus for sufficiently long transit times relative to the supernova delay the two processes tend to converge in their outcomes (but then with little residual radiative output). Again, if both mechanisms exist in equal numbers, $f_{esc-run} = 0.0041$. In these bottom panels we also include from the middle pan-

els the S400 $z_{HM} = 3.4$ result solely for supernova ejection at absorber distance 17 kpc and show this at the lower relative abundance value $[Si/C] = 0.0$, not 0.4 as in the middle panels. It is interesting that for Si II/C II : C II/C IV this encompasses the data points outlying the lowest dynamical ejection curve and enables a better overall fit to the data. Fits closely similar to these for S600 are obtained with a model of boundary radius 500 pc (S500), giving $f_{esc-run} = 0.0099$ and corresponding normalizing absorber distance 8.5 kpc if solely dynamical ejection and $f_{esc-run} = 0.0059$ if both mechanisms contribute equally in numbers.

Here in summary, for the *strong* absorbers the above trials demonstrate the general overwhelming filtering effect on the ultimate stellar spectral contributions by: (a) the runaway process being differentially constrained by the short lifetimes of a wide swathe of massive stars; coupled with (b) the escaping, cooler, stars progressively having the necessary spectral features but limited by diminishing ionizing radiation (Figure 21). At $z_{HM} = 4.4$ these together confine the band of effective stellar contributions to masses $\sim 7\text{--}25 M_{\odot}$. However, at our *lower redshifts* runaway stars are included to the highest stellar masses ($100 M_{\odot}$) although with radiative contributions still moderated in correspondence with loss in active lifetime depending on the character of the escape paths taken. We stress that these are empirical conclusions founded on our observational evidence of the specific, evolving, radiative environments experienced by the strong absorbers in our sample and having apparent properties similar to the CGM absorbers studied by Steidel et al. (2010).

Now concerning the *general metagalactic* ionizing radiation, which we address in the next subsection: at the lower redshifts the runaway process is well able to deliver the output necessary to maintain the ionization of the IGM at the observed levels; however at our higher redshifts we recognize that based on the strong absorbers the residual populations are unable to do this. Consequently, in the following we give attention to the weaker, apparently more highly ionized, absorbers we detect in our sample alongside the strong absorbers.

9.2.2. Contribution to the Metagalactic Ionizing Radiation Background

Above we obtain values for $f_{esc-run}$ on the supposition that both the dominant dynamically ejected and minor supernova ejected runaway mechanisms are included in equal numbers within the 30% total from Tetzlaff et al. (2011), although the actual partition between these currently is uncertain. On this basis, and focusing on our spectral observations of *strong* absorbers containing positively detected C IV, C II, Si IV and Si II, we obtain the values $f_{esc-run} = 0.011$ for the disk model D200 at $z_{HM} = 1.9$ and 2.6, close to the respective values 0.0067 and 0.014 obtained from observed H I photoionization rates in the IGM implied by equation (7). If instead we take the spheroidal model S200, $f_{esc-run} = 0.052$ and if this case better represents components of the observed lumpy structures within galaxies at these redshifts there is considerable radiative margin to accomodate possible reductions in total outcome due to the complex geometry. At $z_{HM} = 3.4$ the spheroidal models S400 and S300 give respective values $f_{esc-run} = 0.012$ and 0.021, with the latter being quite close to the value 0.028 from equation (7); at $z_{HM} = 3.0$ there is correspondence. However, at $z_{HM} = 4.4$ the spheroidal models S600 and S500 yield respectively $f_{esc-run} = 0.0041$ and 0.0059, only about 10% of the value 0.056 from equation (7).

We conclude that the fractions of ionizing radiation given in equation (7) can be emitted in the approximate range $1.9 < z < 3.0$ from galaxies by means of runaway stars produced within galactic structures having respective escape boundary distances of order 200 to 300 pc. At redshifts beyond this there is rapid structural change bringing increasing boundary distances with emitted ionizing radiation falling far short of the level required to maintain the observed concurrent IGM H I photoionization rates.

Nevertheless, it remains that the specific spectral characteristics we obtain in §9.2.1 are strongly required by our empirically derived observations and that in general *the spectrally modified outcomes of the stellar runaway modeling in concept are intrinsically robust and not reliant on special fine-tuning*. In an attempt to raise the emitted ionizing radiation at $z_{HM} = 4.4$ for a given individ-

ual galaxy through a hybrid situation by adding radiation possibly emanating from stars escaping from star-forming regions separated from the boundary by only ~ 200 pc, *mixing* with that from stars traveling from the deeper seated sites already quoted, we find this model quickly is dominated by the hotter stars and so brings the CLOUDY predictions strongly out of step with the observations, as we have already demonstrated in Figure 20(b). We must therefore conclude that there coexists an extended population of relatively low luminosity compact galaxies with typical effective boundary distance $\lesssim 200$ pc, thus individually emitting ionizing radiation with efficiency sufficiently high to accomodate the observed H I ionization rates. Reionization models based on observed UV luminosity functions at high redshifts point to a similar need in order to complete reionization by $z = 6$ (Ouchi et al. 2009; Kuhlen & Faucher-Giguère 2012; Bouwens et al. 2012a; Robertson et al. 2013). Can we identify such a population within our existing data at least within $3.0 < z < 4.4$?

In §8.2 we note that at our higher redshifts there is a relatively large number of components having strong C IV and detected Si IV but only upper limits in C II. Focusing on the interval $3.4 < z < 4.4$, in the upper panels of Figure 24 we show separately the set of Si IV/C IV : C II/C IV observations from Figure 23(b) having one or both of Si IV and C II as upper limits (notice there is no case with *detected* C II and upper limit Si IV) and the set of strong absorbers with detected C IV, C II, Si IV and Si II. We add corresponding CLOUDY model results for the fiducial absorbers exposed to metagalactic ionizing radiation at the bounding redshifts $z_{HM} = 3.4, 4.4$ and local radiation received at the indicated distances from dynamically ejected runaway stars escaping a spheroidal galactic structure having its dense gaseous boundary at radius 200 pc from the centre of star formation (S200), already used at $z_{HM} = 1.9$ and 2.6 (with appropriate metallicity) in Figure 23(b), and in each case placed at the appropriate redshift-related normalizing distance linking with the nominal distances in Figure 20(b) for comparison, as earlier explained. The object is to contrast the distributions of the absorbers relative to the S200 CLOUDY results here with the other models shown in Figure 23(b). It is evident that the upper limit cases mostly identify quite well

with the S200 model while the full detections in the other panel are better contained by the models represented in Figure 23(b). In the lower panels we add the Figure 23(b) related counterpart cases for Si II/Si IV : C II/C IV and Si II/C II : C II/C IV, now integrally including all available upper limits (as noted earlier, in addition to the baseline presence of C IV, the former requires positive detection of Si IV because it is the base for Si II/Si IV and the latter, of C II as the base for Si II/C II). For the former, it can be seen that the values containing C II upper limits fit more closely with the S200 model than do the values for the strong absorbers which certainly require models such as in Figure 23(b). For the latter, the more constrained set of values here relate well only with the models in Figure 23(b).

With computations as before, for a spheroidal galaxy model of boundary radius 200 pc but now at metallicity 0.2 solar appropriate at our higher redshifts, we obtain $f_{esc-run} = 0.056$ if dynamically ejected and supernova ejected runaway mechanisms both are there in equal numbers, which is the same value as given by equation (7) (if entirely dynamically ejected we obtain 0.104). A spheroidal model of boundary radius 100 pc gives $f_{esc-run} = 0.17$ if both mechanisms are included in equal numbers, well above the metagalactic requirement here, and indicative of the potential for extending to higher redshifts. For example, using equation (7) this value is reached at $z \sim 7$.

Guided by the panels in Figure 24 it is possible to see a similar and evolving picture in the panels for the intervals $1.9 < z < 2.6$ and $2.6 < z < 3.4$ in Figure 23(b). In the top panels there is convergence on a transit geometry based on 200 pc and here the strong absorbers are associated with galaxies themselves emitting ionizing radiation at adequate levels to feed the metagalactic background. Within the middle panels this becomes marginal at $z \sim 3$ but now there is a developed buildup of the weaker absorbers we highlight in Figure 24 and which are well able to make up the deficit.

Within the stellar runaway scenario, therefore, we can conclude that our strong absorbers, relating well to apparently similar absorbers in the CGM of galaxies directly observed by Steidel et al. (2010), represent regions around a relatively luminous subset of individual galaxies whose emitted

ionizing radiation is strongly modified by a process which can be explained by the natural transit of runaway stars and galaxy parameters that substantially evolve over our observed range in redshift. We find such galaxies are able to maintain the ionization of the general IGM over redshifts $1.9 < z < 3.0$ but not beyond. We have in addition clear spectral indications for a large population of weaker and consistently more highly ionized absorbing regions also developing over our full observed range in redshift and apparently representing the CGM of a parallel set of galaxies with relatively compact absorbing regions emitting less modified spectra, so having greater radiative efficiency, which collectively dominate the production of metagalactic ionizing radiation at our higher redshifts extending from $z \sim 3$ and on. In particular, these meet the observed IGM H I photoionization requirements not achieved by individual galaxies such as those located with our strong absorbers at z beyond 3.

The stellar runaway model brings possible spectral implications for the galaxy contribution to the Haardt & Madau (2012) QG_{HM} isotropic metagalactic ionizing radiation background used in all our related computations. However, as is now indicated above, the spectral character of $f_{esc-run}$ from the D200/S200 models for $1.9 < z < 2.6$, coupled with inclusion of a dominant contribution from galaxies of similar $f_{esc-run}$ for $3.4 < z < 4.4$ and likewise extending into $2.6 < z < 3.4$, the equivalent runaway-generated radiation background over 1–4 Ryd will be spectrally close to that of QG_{HM} . As is clear in Figure 23(b), this is reinforced by the indications at the 80 kpc perimeter (where the local galaxy contribution is weak in all cases) that the derived CLOUDY results also for these runaway models in general align well with the results for the QG_{HM} models alone.

9.3. Discussion

The evident evolution in escape parameters that we find necessary to explain the ionization conditions in the strong absorbers we observe is a significant empirical indicator of morphological evolution in the population of luminous galaxies with cosmic time over our range $4.4 < z < 1.9$, requiring the distance between dense star-forming regions and the effective outer boundary of the gaseous volume that prevents the escape of ioniz-

ing radiation to become progressively shorter. Observations of relatively luminous galaxies taken as simple structures show the *luminous size* to be evolving in cosmic time with average half-light radius growing from about ~ 1000 pc at $z = 5$ to ~ 2500 pc at $z = 2$, with values at lower luminosity being several 100 pc smaller (Oesch et al. 2010; Ono et al. 2013). For our presumed relatively luminous galaxies we find respective physical stellar escape distances to the outer absorptive boundary over our redshift range in cosmic time to be 600–200 pc. Can these distances be aligned with the apparent luminous dimensions?

Galaxies within the lower redshifts of our range are straightforward to accommodate. A disk structure of observed radius and semi-height 200 pc or less can give a reasonable match to the emissive escape requirements through the runaway process. In this same redshift range, as earlier mentioned, galaxies also frequently exhibit complex structures with multiple sites of dense star formation (Papovich et al. 2005; Law et al. 2007, 2012), which can be regarded nominally as small spheroids with high emissive escape levels and is well accommodated by the runaway process.

Now for the higher redshifts, taking spheroidal structures (or at the least, very “puffy” compact disks) as an approach to obtaining the longer escape paths which we find necessary for the strong absorbers, additional aspects come to the fore. On the one hand, in general the presence of runaway stars manifestly will increase the *apparent* luminous radial profile of galaxies. On the other, at the higher redshifts where the metagalactic ionizing radiation is stronger, there will be significant fully-ionized inverse Strömgren regions (e.g., Dove & Shull 1994) which effectively reduce inwards the distance from the edge of the *absorptive* H I boundary to the site of star-formation. Together these factors in their effect could bring to physical convergence the measured apparent luminous dimension of galaxies and the stellar radial escape dimensions fitting our conclusions for relatively luminous galaxies which require up to 500–600 pc, shown in Figure 23. Such factors apply equally for the inferred coexisting population of galaxies having relatively lower luminosity, therefore intrinsically more compact, requiring typical escape distance 200 pc or less, shown in Figure 24.

In support of the runaway scenario it is worth

mentioning the work of Gnedin et al. (2008) who model the *radiative* escape of ionizing radiation from galaxies over $3 < z < 9$ using three-dimensional radiative transfer simulations with star formation and feedback (including via supernova explosions). Overall they find rather small values and for disk galaxies at $z \sim 3$ show that at lower galactic masses young stars are embedded deep in the neutral disk because the density and pressure required for star formation is reached only in a very thin (100–200 pc) region near the midplane, while at higher masses the disk is denser and star formation also occurs in regions closer to the outer edge. Interestingly for our own conclusions, they find the absolute escape fraction is negligible in the former, while only mildly positive in the latter due mostly to a small fraction of stars near the edge of the H I boundary *becoming exposed* through their “normal” movement (i.e., with low velocities, not as runaways) and equally so exposed by gross relative oscillation of the stars and the gaseous galactic disk. However, the necessary exposure of stars beyond the H I boundary can be achieved by strongly *aiding the movement* of stars as comes naturally in the runaway process we apply here.

Conversely, as an example already recounted in §8.6, Yajima et al. (2011) in their simulations find that at $z = 3$ –6 the escape fraction increases as the halo mass decreases due to supernova-induced conical regions of highly ionized gas which allow ionizing radiation to escape more easily than in high mass cases. For our strong absorber population we give empirical evidence in §8.6 and §9.2 that the progressive spectral outcomes from such a porosity approach over our range $1.9 < z < 4.4$ do not represent well the escape of ionizing radiation from luminous galaxies having, as shown by Steidel et al. (2010), absorbers within their CGM similar to the strong absorbers in our sample.

However we cannot thus exclude a porosity mechanism for our weaker absorbers, highlighted in Figure 24. While we show the runaway process can account both for the ionization state of these and the spectrally implied radiative contribution to keep the Universe ionized up to high redshifts, this may also apply to the porosity case for low mass, high redshift galaxies. Both mechanisms acting together in such circumstances then is to be expected.

10. SUMMARY

From high resolution spectral observations of nine QSOs (Table 1, Figure 1) we compile a large sample of metal-line systems identified as C IV absorbers outside the Lyman forest in the redshift range $1.6 \lesssim z \lesssim 4.4$ and include Si IV, C II, Si II and N V in these where available. By Voigt profile-fitting procedures using VPFIT (Carswell et al. 2002) we can closely represent these multi-phase systems as complexes of co-existing “single-phase-ionization” component regions (Figures 2, 4, 5, 6). We obtain column densities or upper limits for individual component ions of each species, with Doppler parameters for C and in selected cases for Si (Tables 2–10). Both for components and systems we study statistical distributions, clustering properties and ionization properties, and trace their evolution in redshift. Using combinations of ionic ratios as probes of the radiation environment we study the escape of ionizing radiation from galaxies, bearing on the ongoing cosmic ionization of the IGM, and introduce and develop a new process which we find necessary to enable the models successfully to meet the observations.

In all, we arrive at the following principal conclusions:

1. The C IV *component* column density and Doppler parameter number distributions (Figures 7(a) 10, 11), *system* column density and velocity spread number distributions (Figures 7(a), 11), and differential column density distributions of components and systems (Figure 13), show no significant evolution over the observed redshift range.
2. The C IV *system* total number per unit redshift and total column density per unit redshift also show no significant evolution over the observed redshift range (Figure 9(a)). We find a mean C IV comoving mass density $\langle \Omega_{\text{C IV}} \rangle = (3.44 \pm 1.24) \times 10^{-8}$ (1σ uncertainty limits) (Figure 9(b)). Si IV presents a similar evolutionary picture (Figures 7(b), 9(a)), with a mean comoving mass density $\langle \Omega_{\text{Si IV}} \rangle = (1.23 \pm 0.66) \times 10^{-8}$ (Figure 9(b)). Both are in broad agreement with Songaila (2001; 2005). C II, Si II and N V change substantially with redshift, heralding changes in ionization state (Figures 7(b), 9).
3. We confirm for consistency that absorbers physically close to the sightline QSOs ($\lesssim 3000 \text{ km s}^{-1}$ from the QSO redshifts) have characteristics of

gas illuminated by relatively hard radiation (Figure 8).

4. The C IV *components* exhibit strong clustering out to velocity separations $\lesssim 300 \text{ km s}^{-1}$ for our uniform statistical sample and to $\lesssim 400 \text{ km s}^{-1}$ with the addition of some systems with densely complex components but for both there is no clustering signal detected for *systems* on any scale from 150 km s^{-1} out to 50000 km s^{-1} (Figure 14). Neither of these (one-dimensional) distributions shows similarities with galaxy clustering (Figure 15). We argue that the results from our data are entirely due to the peculiar velocities of gas present in the outer extensions of galaxies (probed in the confined sightlines to the background QSOs, and which in general do not encounter more than one galaxy in a given cluster or group.

5. We find no significant change in the component or system median column density ratio Si IV/C IV with redshift and in particular no large change near $z = 3$ (Figure 16(a)), contrary to previous observations coupled with claims that this can indicate the onset of complete reionization of He II. The component ratio Si II/C II is similarly unchanging while C II/C IV, Si II/Si IV and N V/C IV vary (continuously) with redshift (Figure 16(b)). However, individually these are only partial indicators of ionization state.

6. Using the four combinations of ionic ratios Si IV/C IV : C II/C IV, N V/C IV : C II/C IV, Si II/Si IV : C II/C IV and Si II/C II : C II/C IV we compare our observations of the *strong* absorbers with model ionization predictions using the CLOUDY code (version C10) for absorbers exposed to the empirically founded evolving metagalactic ionizing radiation background (Haardt & Madau 2012) due to the cosmologically distributed contributions of QSOs and galaxies (Figure 17(a)). While good fits are obtained at our lowest redshifts ($z \lesssim 2.6$) where QSOs dominate the metagalactic ionizing radiation, it is apparent that simultaneously consistent fits to our ionic ratio combinations over the full redshift range, and in particular at our highest redshifts, cannot be achieved with this model alone (Figures 17(b), 23(b)).

7. With simple modification to the cosmic radiation model (Haardt & Madau 2012; Haardt 2014), we investigate the possible effect of delayed reionization of intergalactic He II, not formally in-

cluded in its geometrical complexity in the original model, and find that this too cannot explain our observations (Figures 17(a), (b)).

8. We model the effect of collisional ionization of the absorbers in the presence of the metagalactic ionization radiation background (Figure 18) and conclude that the great majority of the absorbers in our sample are in or close to a state of photoionization equilibrium, confirming the procedures used in our radiation modelling. Also we investigate the effects of changes of metallicity and H I column density in our model absorbers (Figure 19) and find that the observed systematic evolutionary effects exhibited in the ionic ratios are not caused simply by changes in absorber properties.

9. Our data support the presence in the absorbers of a range in relative abundance $[\text{Si}/\text{C}] \sim 0.0\text{--}0.4$, consistent with α -element enhancement in galactic metal-poor stars (Figures 17(b), 23(b)).

10. Our conclusions in points 6–8 sharply narrow the cause of the evolving ionization state in the absorbers we observe to substantial *spectral changes* in their *local* ionizing radiation environment, not included in previous work. In the remaining summary we outline the path leading to a new radiative process which enables the empirical convergence over our full range in redshift of our ionization modeling with our observations of the absorbers in our sample. Focusing first on our *strong* component absorbers with positive detections of C IV, Si IV, C II and Si II, we seek only to match the *spectral* outcomes of our modeling with the spectrally-induced signatures within our observed ionic ratio combinations to arrive at *empirically* implied structurally-related geometrical properties of the *associated* local galaxies. Following this we include our *weaker* component absorbers in consideration of the production of the necessary ionizing radiation *levels* to maintain the evolving ionization rate of the general IGM observed throughout our range in redshift.

11. On the recognition that absorbers such as the strong components in our sample represent regions located within a galactic CGM (Steidel et al. 2010), and with our clustering observations more generally also consistent with this (point 4), we augment the metagalactic background radiation with *proximity* radiation escaping from star-forming regions in the locally sited galaxy. A general resort to explain the escape of

a fraction of stellar ionizing radiation from inside such highly attenuating environments is the formation of supernova-generated transparent channels through which some of the radiation can pass, largely spectrally unmodified. For a local galaxy component we employ Starburst99 (Leitherer et al. 1999, 2010) to model a galaxy with Salpeter (1955) IMF undergoing continuous star formation, producing an intrinsic spectral energy distribution similar to those applied in Haardt & Madau (2012), then relate this to observed luminosities in the non-ionizing far-ultraviolet and apply the evolving escape fraction used by Haardt & Madau over 1–4 Ryd in context of the metagalactic background. We place our absorbers at the typical distances 20 and 80 physical kpc from the local galaxies (Steidel et al. 2010) and add the received radiative contributions to the evolving metagalactic ionizing background spectrum before the CLOUDY modeling. While reasonable fits to our full data set are obtained at our lower redshifts, in extension to higher redshifts there is increasing divergence from our data for the strong absorbers and taken collectively we find the fit to our data now becomes very significantly *poorer* than before (Figure 20). We conclude that this *geometrical* model describing the escape of Lyman continuum radiation, by itself, is *not a viable representation* for our strong absorbers.

12. We therefore move to a more kinematically-dependent scenario in which the passive escape of ionizing radiation into the IGM is transformed into the dynamic escape of the ionizing *sources* themselves. It is established that a significant fraction of all stars in the Galaxy are moving with higher than usual velocities, ejected as “runaway stars” from dense young stellar systems not long after their birth. Depending on the placing of a given star-forming region in the galaxy, the most massive stars, having the shortest main sequence lifetimes, may not escape at all from the boundary of galactic absorption, while longer-living lower mass stars can spend a fraction of their main sequence lifetimes in relatively clear space. We develop this considerably further by exploiting in detail the resulting *spectral* changes in the final efflux of radiation that are induced.

13. We model the runaway-modified galactic spectral energy distribution in the Lyman continuum by use of Starburst99 with the same overall

parameters as applied in point 12, but since the radiative product of the runaway process is dependent on stellar mass we now segment the full mass range into narrow slices within the underlying Salpeter IMF and compute a set of individually-derived population synthesis spectra which collectively cover the same mass range as before. Then we associate each component spectrum with the fraction of main sequence lifetime remaining after escape for a set of escape intervals stemming from a defined stellar velocity distribution and trial galactic escape boundary distances. In this we consider star-forming sites in both spheroidal and disk-like galactic structures and include geometrical factors to assess the unshadowed radiative aspect at the absorbers for stars when escaping, and obtain the aggregated resultant spectral outcomes including both dynamically ejected and delayed supernova ejected runaways. As in point 12 we combine these with the metagalactic background radiation at each redshift before CLOUDY modeling.

14. By iterative trials making comparison with our observations of the strong absorbers in our sample we find different geometries are indicated for each redshift interval in a pattern evolving with redshift, with a balance to contributions from higher stellar masses increasing with cosmic time. The spectra at the higher redshifts now feature a deep He I ionization discontinuity and diminishing strength to higher energies, characteristic of stars having mass around $20 M_{\odot}$ and lower (Figures 21, 23(a)). The He I discontinuity is the dominant feature providing the necessary changes to bring together the predicted and observed ionic ratio combinations for our strong absorbers at our higher redshifts. At our lower redshifts, runaway stars present to the highest stellar masses ($100 M_{\odot}$) are needed to match the data for the strong absorbers although with radiative contribution still moderated in correspondence with loss in active lifetime depending on the character of the transit escape paths. Taking all redshift intervals together there is now a good match to these data over our full range in redshift (Figure 23(b)). The evolution in escape parameters is a significant indicator of morphological evolution in the population of the associated galaxies, requiring the positions of dense star-forming regions and the effective boundaries of the gaseous volume to become

progressively closer with cosmic time.

15. Within the stellar runaway scenario we can conclude that our *strong* absorbers, relating well to apparently similar absorbers in the CGM of galaxies directly observed by Steidel et al. (2010), represent regions around a relatively luminous subset of individual galaxies whose emitted ionizing radiation is strongly modified by a process which can be explained by the natural transit of runaway stars with parameters that substantially evolve over our observed range in redshift. We stress that these are empirical conclusions founded on our observational evidence of the specific, evolving, radiative environments experienced by the strong absorbers in our sample.

16. Now coming to direct consideration of the *general metagalactic* background ionizing radiation, we find that galaxies corresponding to those associated with the strong absorbers in the conclusions above have radiative escape fractions at energies higher than 1 Ryd able to maintain the ionization of the general IGM over redshifts $1.9 < z < 3.0$ but not beyond. However, alongside the strong absorbers, we have in our data additional spectral indications for a large population of weaker and consistently more highly ionized absorbing regions (detected with upper limits in C II) apparently representing the CGM of a parallel set of more compact galaxies having much greater radiative efficiency (Figure 24), rapidly developing in proportion to the strong absorbers over our observed redshift range (Figure 23(b)). In particular, through the runaway process these individually can reach radiative escape fractions at 1 Ryd that exceed the recognized level needed to maintain the IGM ionized at $z = 4.4$. This population also can contribute significantly to the production of metagalactic ionizing radiation over our lower redshifts then dominate at $z \sim 3$ and beyond, collectively meeting the observed IGM H I photoionization requirements over our full range in redshift.

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TABLE 1
LOG OF OBSERVATIONS

Object	z_{em} ^a	V(R) ^b mag	Dates ^c	λ -Range ^d Å	Exposure ^e s	FWHM ^f km s ⁻¹	S/N ^g
Q1626+6433	2.32	15.8	1995 05 19 — 1996 07 22	3580 — 6179 ^h	24063	6.6	88 — 128 — 137
Q1442+2931	2.66	16.0	1994 06 12 — 1995 06 21	3624 — 6150 ^h	22500	6.6	113 — 107 — 121
Q1107+4847	2.97	16.6	1994 12 26 — 1995 02 22	3643 — 6663	26000	6.6	90 — 94 — 81
Q0636+6801	3.18	16.4	1993 11 13 — 1995 02 22	3643 — 6663	36200	6.6	112 — 107 — 100
Q1425+6039	3.18	16.2	1995 05 18 — 1995 05 19	3736 — 6540	37200	6.6	168 — 140 — 113
Q1422+2309C	3.63	17.3	1998 02 01 — 1999 04 14	3569 — 7347	51200	4.4	92 — 90 — 61
Q1645+5520	4.10	17.0	1997 05 09 — 1997 05 30	4557 — 8123	72200	6.6	102 — 119 — 81
Q1055+4611	4.15	16.9	1995 04 07 — 1996 05 24	4587 — 8009	27037	6.6	71 — 47 — 31
Q2237–0607	4.56	18.3	1994 10 10 — 1995 08 21	4933 — 8800	54000	6.6	62 — 42 — 28

^aRedshifts largely obtained from the literature, supplemented by the positions of the onset of the Lyman forest and the peak of the Lyman α emission line in the HIRES spectrum.

^bQ2237–0607 has R mag; the rest have V mag.

^cTotal period over which the observations were made.

^dTotal available wavelength range, extending from within the Lyman forest to beyond the C iv emission line.

^eTotal time spent on the collection of exposures.

^fThese are approximate values. Along the echelle orders the velocity resolution differs from the mean by $\sim \pm 3.8\%$.

^gS/N over three pixels (roughly equal to a resolution element for all but Q1422+2309C) outside the Lyman forest sampled near the three wavelengths $\lambda\lambda 1270, 1380, 1500$ in the rest frame of the QSO: by avoiding the main emission lines these tend to conservative estimates.

^hIn subsequent observations used here coverage of the Lyman forest is extended to ~ 3200 Å.

TABLE 2
HEAVY ELEMENT ABSORPTION LINES: Q1626+6433 $z_{em} = 2.32^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
1.779								
1.778611	11.5	...	1.91 ± 0.18	...	...	...	...	1
1.778811	4.4	...	0.55 ± 0.13	...	...	...	...	2
1.778988	9.9	...	3.33 ± 0.20	...	...	...	...	3
1.779124	7.0	...	7.40 ± 0.20	...	...	...	...	4
1.779316	10.8	...	17.8 ± 0.3	...	...	...	...	5
1.779536	10.5	...	4.99 ± 0.20	...	...	...	...	6
1.779771	4.7	...	0.42 ± 0.13	...	...	...	...	7
1.780041	6.5	...	0.68 ± 0.14	...	...	...	...	8
1.780331	9.3	...	7.07 ± 0.19	...	...	...	...	9
1.817								
1.816490	16.2	...	13.4 ± 0.5	...	...	...	...	1
1.816527	7.0	...	23.7 ± 0.5	...	...	...	...	2
1.816715	6.2	...	10.7 ± 0.2	...	...	...	...	3
1.816823	7.5	...	23.9 ± 0.3	...	...	...	...	4
1.816977	11.2	...	1.34 ± 0.20	...	...	...	...	5
1.843								
1.842835	11.6	...	2.52 ± 0.23	...	...	...	...	1
1.842971	20.4	...	2.44 ± 0.29	...	...	...	...	2
1.847								
1.846881	12.4	...	0.72 ± 0.18	...	...	...	...	1
1.847040	4.3	...	1.39 ± 0.13	...	...	...	...	2
1.847159	8.9	...	1.97 ± 0.16	...	...	...	...	3
1.880 ^a								
1.879914	5.6	...	1.39 ± 0.16	...	...	...	...	1
1.879991	4.5	...	2.70 ± 0.16	...	...	...	...	2
1.880131	5.4	...	1.58 ± 0.14	...	...	...	...	3
1.880287	7.4	...	1.22 ± 0.17	...	...	...	...	4
1.927 ^b								
1.925731	13.9	(12.8)	13.3 ± 0.5	35.8 ± 3.6	3.10 ± 1.77	...	...	1
1.925743	4.7	(4.1)	7.28 ± 0.35	31.8 ± 2.3	4.39 ± 1.14	...	...	2
1.925874	7.4	(5.9)	13.1 ± 0.3	51.9 ± 1.7	8.53 ± 0.89	...	...	3
1.926006	9.8	(6.9)	17.9 ± 0.3	31.5 ± 1.4	...	...	...	4
1.926185	8.7	(7.1)	18.5 ± 0.3	53.2 ± 1.5	...	...	...	5
1.926349	9.2	(6.6)	38.7 ± 0.9	52.0 ± 1.8	...	...	...	6
1.926478	10.6	(9.1)	16.0 ± 0.6	58.4 ± 2.1	...	15.0 ± 4.5	...	7
1.926632	6.2	(4.8)	4.13 ± 0.61	24.6 ± 2.9	...	141 ± 8	...	8
1.926703	21.2	(20.5)	28.2 ± 1.9	175 ± 8	...	64.4 ± 20.3	...	9
1.926733	6.4	(5.1)	12.7 ± 0.6	41.4 ± 2.7	...	37.8 ± 5.8	...	10
1.926791	6.3	(4.9)	2.85 ± 0.62	7.03 ± 2.63	$[145 \pm 67]$	185 ± 8	...	11
1.927016	10.9	(9.5)	28.2 ± 0.5	153 ± 2	188 ± 21	532 ± 8	...	12
1.927203	9.1	(6.7)	52.6 ± 1.6	163 ± 3	91.9 ± 10.3	88.1 ± 3.5	...	13
1.927299	7.5	(5.8)	34.8 ± 1.8	167 ± 4	43.6 ± 5.1	62.3 ± 3.4	...	14
1.927498	17.0	(16.1)	74.7 ± 1.7	248 ± 5	20.8 ± 7.1	53.3 ± 7.3	...	15
1.927552	7.2	(6.0)	2.30 ± 0.78	76.8 ± 4.3	$[264 \pm 40]$	287 ± 7	...	16
1.927659	8.6	(7.6)	2.22 ± 0.34	13.2 ± 1.6	21.6 ± 2.0	38.2 ± 3.3	...	17
1.927852	14.5	(13.4)	23.6 ± 0.4	39.0 ± 1.2	8.16 ± 1.16	...	...	18
1.928104	18.1	(17.3)	8.92 ± 0.24	13.0 ± 1.3	...	...	...	19
2.048 ^c								
2.047870	13.4	(12.2)	10.7 ± 0.2	< 0.90	< 0.43	...	...	1
2.048096	6.9	(5.8)	2.36 ± 0.16	< 0.68	< 0.33	...	...	2
2.048277	3.1	(2.1)	0.60 ± 0.12	< 0.57	< 0.26	...	...	3
2.056 ^d								
2.054804	20.6	(19.8)	8.29 ± 0.25	< 2.08	...	...	...	1
2.055106	8.2	7.4	17.1 ± 0.3	19.8 ± 1.1	2.10 ± 0.42	...	...	2
2.055356	10.0	8.8	57.5 ± 0.6	51.1 ± 1.4	4.15 ± 1.22	...	...	3
2.055439	54.6	(54.3)	19.3 ± 0.5	9.00 ± 1.16	...	...	...	4

TABLE 2—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.055492	9.4	(7.6)	11.9 ± 0.8	< 4.43	...	...	...	5
2.056236	4.1	(2.9)	0.45 ± 0.11	< 0.89	...	...	...	6
2.069								
2.069272	11.4	(10.0)	1.86 ± 0.13	1.71 ± 0.83	< 0.42	...	...	1
2.099 ^e								
2.097631	8.3	(6.7)	2.38 ± 0.15	< 0.74	< 0.37	...	...	1
2.097875	5.9	(5.2)	10.7 ± 0.2	5.01 ± 1.15	0.64 ± 0.36	...	...	2
2.097977	3.7	(2.4)	1.14 ± 0.17	3.02 ± 0.93	< 0.35	...	...	3
2.098043	21.9	(21.2)	15.4 ± 0.3	3.30 ± 2.44	< 0.78	...	...	4
2.098433	3.7	(2.4)	0.42 ± 0.11	< 0.46	< 0.27	...	...	5
2.098740	7.6	(6.5)	2.33 ± 0.14	4.02 ± 0.70	< 0.35	...	...	6
2.098945	4.3	(3.6)	9.93 ± 0.20	3.16 ± 0.54	< 0.34	...	...	7
2.099050	9.2	(7.3)	13.6 ± 0.2	1.81 ± 0.67	< 0.42	...	...	8
2.099317	3.7	(2.4)	1.03 ± 0.14	< 1.07	< 0.36	...	...	9
2.099406	19.0	(18.1)	7.65 ± 0.27	< 1.13	< 0.66	...	...	10
2.099903	17.2	(16.4)	0.54 ± 0.19	< 0.92	< 0.61	...	...	11
2.110 ^f								
2.108103	17.3	(16.3)	0.55 ± 0.16	< 0.89	...	...	...	1
2.109149	5.6	4.4	17.4 ± 0.3	81.5 ± 1.6	21.1 ± 1.0	16.7 ± 2.7	...	2
2.109168	26.4	(25.4)	3.89 ± 0.35	< 1.86	...	...	...	3
2.109378	4.7	4.4	3.59 ± 0.13	16.9 ± 0.7	...	...	...	4
2.109494	5.1	3.4	1.37 ± 0.12	9.28 ± 0.60	7.84 ± 0.46	13.9 ± 1.9	...	5
2.109604	9.1	(4.5)	1.95 ± 0.15	4.29 ± 0.57	2.61 ± 0.48	...	...	6
2.109749	6.8	(5.4)	1.34 ± 0.13	7.31 ± 0.64	2.58 ± 0.38	4.63 ± 2.08	...	7
2.109938	18.2	(17.4)	3.67 ± 0.21	2.89 ± 1.06	< 0.64	...	...	8
2.110120	5.8	(4.2)	5.43 ± 0.15	20.9 ± 0.8	22.5 ± 0.8	19.7 ± 1.2	...	9
2.110213	4.6	(2.9)	4.63 ± 0.16	15.8 ± 0.7	98.2 ± 6.5	286 ± 7	...	10
2.110289	3.6	(2.8)	2.45 ± 0.13	7.22 ± 0.58	2.39 ± 0.64	2.42 ± 0.89	...	11
2.110398	6.1	(4.5)	4.23 ± 0.14	9.20 ± 0.60	3.80 ± 0.39	...	...	12
2.110506	6.1	(4.2)	0.97 ± 0.12	< 0.78	4.34 ± 0.36	7.95 ± 0.88	...	13
2.110688	6.7	(5.1)	1.12 ± 0.18	3.58 ± 0.67	6.16 ± 0.56	5.85 ± 0.88	...	14
2.110734	3.1	(2.0)	0.75 ± 0.15	7.07 ± 0.76	< 0.45	...	...	15
2.110907	11.1	(9.7)	2.15 ± 0.26	< 2.08	< 1.04	...	...	16
2.111442	7.4	(5.8)	1.20 ± 0.11	< 0.63	< 0.34	...	...	17
2.208								
2.208260	9.1	(7.3)	0.62 ± 0.12	< 0.68	< 0.41	...	...	1
2.208462	8.6	(6.7)	4.84 ± 0.13	< 0.67	< 0.40	...	...	2
2.244 ^g								
2.242553	4.0	3.0	5.76 ± 0.12	5.74 ± 0.46	2.99 ± 0.29	1.86 ± 0.34	...	1
2.242713	13.7	(12.6)	15.6 ± 0.2	2.57 ± 0.69	0.60 ± 0.42	< 0.59	...	2
2.243085	5.3	(4.0)	0.60 ± 0.17	2.24 ± 0.74	1.20 ± 0.45	0.74 ± 0.55	...	3
2.243097	15.8	(14.8)	8.30 ± 0.26	< 1.21	< 0.73	< 0.89	...	4
2.243599	15.7	(14.7)	0.93 ± 0.14	< 1.52	< 0.42	< 1.31	...	5
2.243834	5.0	(3.9)	0.95 ± 0.09	< 0.73	...	< 0.39	...	6
2.244101	7.8	7.5	13.5 ± 0.2	7.76 ± 0.58	2.36 ± 0.33	1.58 ± 0.45	1.07 ± 0.42	7
2.244483	8.4	(6.5)	27.6 ± 0.4	3.46 ± 0.97	< 0.61	...	6.57 ± 0.75	8
2.244609	32.7	(32.2)	14.8 ± 0.9	< 3.66	< 1.76	...	24.3 ± 2.4	9
2.244682	7.9	(5.7)	$[96.2 \pm 1.2]$	21.6 ± 1.0	0.69 ± 0.56	...	8.71 ± 0.80	10
2.244786	4.6	3.3	...	5.76 ± 0.62	< 0.38	...	2.16 ± 0.38	11
2.244943	15.0	(14.0)	$[282 \pm 7]$	40.5 ± 1.3	0.81 ± 0.66	...	24.0 ± 0.8	12
2.245051	3.3	(2.7)	14.1 ± 2.9	6.52 ± 0.62	2.54 ± 0.34	< 0.51	...	13
2.245173	2.7	1.8	...	10.3 ± 0.7	< 0.39	< 0.33	...	14
2.245253	8.3	5.1	70.4 ± 0.6	11.4 ± 0.8	< 1.87	< 0.52	9.16 ± 0.45	15
2.245413	19.9	(19.5)	0.89 ± 0.20	< 1.01	< 6.24	...	...	16
2.285 ^h								
2.284657	11.2	(9.8)	0.62 ± 0.14	< 0.51	< 0.34	< 0.43	0.58 ± 0.32	1
2.285080	4.5	3.2	17.8 ± 0.7	36.4 ± 1.3	5.62 ± 0.70	2.65 ± 0.70	< 0.62	2

TABLE 2—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.285087	9.9	(8.7)	20.5 ± 0.5	12.9 ± 1.2	< 0.87	< 0.95	4.80 ± 0.83	3
2.285347	6.1	(5.0)	14.7 ± 0.2	1.08 ± 0.46	0.39 ± 0.32	< 0.36	3.82 ± 0.31	4
2.285440	5.3	2.9	11.2 ± 0.2	7.54 ± 0.47	3.22 ± 0.33	1.82 ± 0.34	< 0.27	5
2.285592	7.8	(6.4)	1.39 ± 0.12	< 0.48	< 0.31	< 0.36	1.64 ± 0.29	6
2.291 ⁱ								
2.289840	3.9	(3.3)	< 0.10	1.34 ± 0.46	10.8 ± 0.4	12.5 ± 0.6	< 0.31	1
2.290023	21.4	(20.7)	6.94 ± 0.24	29.9 ± 1.1	25.8 ± 0.8	19.9 ± 0.9	< 0.69	2
2.290181	5.1	(5.2)	2.11 ± 0.16	12.1 ± 0.8	12.9 ± 0.6	14.3 ± 0.7	< 0.40	3
2.290256	16.8	(15.9)	7.73 ± 0.28	23.7 ± 1.3	6.03 ± 0.82	< 1.26	< 0.81	4
2.290508	11.6	(10.3)	3.17 ± 0.28	< 1.01	< 0.66	< 0.72	< 0.83	5
2.290583	6.8	(5.9)	1.80 ± 0.21	7.69 ± 0.78	2.05 ± 0.49	\dots	< 0.52	6
2.290746	3.1	(2.0)	0.15 ± 0.14	1.16 ± 0.54	3.86 ± 0.40	3.25 ± 0.48	\dots	7
2.290866	15.3	(14.3)	2.69 ± 0.46	< 1.53	< 1.11	< 1.17	\dots	8
2.290927	6.3	5.4	0.46 ± 0.27	4.99 ± 0.93	16.7 ± 0.7	17.8 ± 0.9	\dots	9
2.291421	3.6	2.3	5.80 ± 0.13	13.0 ± 0.5	4.60 ± 0.28	5.50 ± 0.40	\dots	10
2.291573	10.0	(8.4)	19.4 ± 0.3	5.32 ± 0.69	0.68 ± 0.43	< 0.61	< 0.92	11
2.291724	5.5	(4.9)	22.3 ± 0.4	43.2 ± 0.9	12.9 ± 0.5	7.90 ± 0.64	< 0.61	12
2.291836	3.5	(3.1)	15.2 ± 0.5	31.2 ± 0.9	27.3 ± 0.9	25.4 ± 1.2	< 0.54	13
2.291866	32.1	(31.6)	68.8 ± 0.9	17.4 ± 2.7	< 1.99	\dots	13.6 ± 2.3	14
2.291906	7.4	(6.4)	16.7 ± 0.5	23.7 ± 1.2	10.1 ± 0.7	6.65 ± 1.16	< 0.91	15
2.292207	5.0	3.4	1.67 ± 0.14	5.75 ± 0.50	9.38 ± 0.36	10.7 ± 1.2	< 0.47	16
2.292370	6.8	(5.6)	1.46 ± 0.12	< 0.46	< 0.27	\dots	< 0.60	17
2.321 ^j								
2.320312	5.8	(5.1)	4.78 ± 0.14	8.39 ± 0.50	< 0.34	< 0.44	< 0.52	1
2.320398	6.2	(5.4)	5.37 ± 0.16	3.01 ± 0.51	< 0.36	< 0.39	< 0.26	2
2.320591	16.8	(15.9)	10.2 ± 0.2	1.73 ± 0.67	\dots	< 0.52	< 0.37	3
2.321017	19.4	(18.7)	1.18 ± 0.16	< 0.70	\dots	< 0.53	< 0.72	4
2.323 ^k								
2.322443	15.0	(14.0)	5.12 ± 0.15	< 1.15	\dots	< 0.53	0.86 ± 0.31	1
2.322665	7.9	(6.5)	4.43 ± 0.12	< 0.63	\dots	< 0.38	< 0.23	2
2.322896	6.9	(6.3)	0.55 ± 0.10	< 0.42	\dots	< 0.50	< 0.22	3
2.323238	19.0	(18.2)	6.49 ± 0.21	< 1.93	\dots	< 0.65	< 0.40	4
2.323344	5.4	(4.7)	3.34 ± 0.14	1.92 ± 0.39	< 0.50	< 0.37	< 0.30	5
2.323611	18.2	(17.4)	8.13 ± 0.17	< 1.21	< 0.86	< 0.56	0.67 ± 0.34	6
2.324029	9.9	(8.2)	2.78 ± 0.12	< 0.46	< 0.31	< 0.43	< 0.32	7

*See Figures 1, 2, 4 and 6.

^aComponent 4 of C IV $\lambda 1551$ coincides with Si II $\lambda 1527$ at $z = 1.927$ and is not used but $\lambda 1548$ is clear.

^bThis complex system has very strong C II and Si II and weak C IV in components 11 and 16: from the extent of the H I Lyman α wings associated with these the limit on the combined column densities is $\log N(\text{H I}) \lesssim 18.7$. Si IV $\lambda 1394$ contains weak N V $\lambda 1239$ at $z = 2.291$ and C II at $z = 2.056$ but $\lambda 1403$ is clear. Si II values come from $\lambda 1527$; $\lambda 1260$, in the forest, gives a consistent fit to the data (shown in Figure 4). Although C II is in the forest useful values are obtained for all components except 4–10, for which comparison with Si II suggests have substantial underlying H I (see Figure 4), and component 19 which is weak and may be significantly contaminated; furthermore, the strong components 11 and 16 are mildly saturated and the values, given in square brackets, are highly approximate. An anomalous, weak, narrow feature appearing at $z = 1.927950$ in C II and another at $z = 1.926104$ in Si II, not detected in the other species, are indicated in Figure 4 but not included in the table.

^cC II is outside the forest.

^dSi IV $\lambda 1394$ is blended with very weak Ni II $\lambda 1455$ at $z = 1.927$ but $\lambda 1403$ is clear. C II is largely blended with Si IV $\lambda 1394$ at $z = 1.927$ and broad N V $\lambda 1239$ at $z = 2.291$ but components 2 and 3 have good values; component 6, which seems to appear in the VPFIT analysis (see Figure 4), is too uncertain to use. Si II is available only in $\lambda 1527$ and too weak to yield useful measures or upper limits here.

^eSi IV $\lambda 1394$ is blended with strong Al III $\lambda 1855$ at $z = 1.328$ and values come mostly from $\lambda 1403$.

^fIn this complex system component 10 is very strong in C II and Si II and relatively weak in C IV: mild damping wings centred on this position appear to be present in the H I Lyman α profile and indicates $\log N(\text{H I}) \sim 18.3$. Si IV $\lambda 1394$ is peripherally blended with Al III $\lambda 1863$ at $z = 1.328$, and C IV $\lambda 1548$ in the $z = 1.817$ system encroaches slightly on $\lambda 1403$, but together good values are obtained for all components. C II contains Si II $\lambda 1260$

at $z = 2.291$ but in the main separation of these is straightforward (see Figure 4). Si II $\lambda 1260$ is in the forest where it is partially clear (although here blended with very weak Si II $\lambda 1193$ at $z = 2.285$) and together with the strong $\lambda 1527$ (see Figure 4) self-consistent values are obtained for the listed components.

^gThis complex system has relatively high ionization. C IV $\lambda 1548$ contains weak Si II $\lambda 1527$ at $z = 2.291$ but $\lambda 1551$ is clear; components 10–12 and 14 are strongly saturated in $\lambda 1548$ and close to saturation or too uncertain in $\lambda 1551$ and the two determined values (in square brackets), despite the apparent small errors, must be considered as highly approximate. Si II $\lambda 1260$ is outside the forest but is generally weak and partially mixed with N V $\lambda 1243$ at $z = 2.291$, making some component values too uncertain to use. N V is in the forest but relatively strong and some useful values are obtained using both members of the doublet.

^hC IV $\lambda 1551$ is blended with weaker C IV $\lambda 1548$ at $z = 2.291$ but $\lambda 1548$ is clear. N V is outside the forest.

ⁱIn this is a complex system component 1 is narrow and relatively strong in C II and Si II while undetected in C IV but the H I Lyman α profile gives only $\log N(\text{H I}) \lesssim 15.8$. Component 13 also is narrow and in C II and Si II is the strongest in the system; while C IV is also quite strong, mild H I Lyman α damping wings centred on this component yields $\log N(\text{H I}) \sim 17.7$. C IV $\lambda 1548$ includes very weak Ni II $\lambda 1742$ at $z = 1.927$ and strong C IV $\lambda 1551$ at $z = 2.285$ but $\lambda 1551$ is clear. Many of the smaller values for $b(\text{C})$ are from C II. Si II $\lambda 1260$ is partially blended with C II at $z = 2.110$ making values for components 14 and 17 too uncertain to include; additionally, component 6 appears significantly contaminated and is not used. N V $\lambda 1239$ is blended with C II at $z = 2.056$ and strong Si IV $\lambda 1394$ at $z = 1.927$ and $\lambda 1243$ is somewhat contaminated with weak Si II $\lambda 1260$ at $z = 2.244$; only the more certain values are listed.

^jThis is close to z_{em} . In components 3 and 4 C II seems contaminated, possibly with weak absorption related to nearby Al III $\lambda 1855$ at $z = 1.390$, and values are not included.

^kThis is close to z_{em} and may be associated with the $z = 2.321$ system. C II is heavily blended with Mg II $\lambda 2796$ at $z = 0.586$, masking components 1–4.

TABLE 3
HEAVY ELEMENT ABSORPTION LINES: Q1442+2931 $z_{em} = 2.66^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
1.910								
1.910407	7.9	...	2.12 ± 0.12	...	...	...	...	1
1.910582	3.6	...	0.53 ± 0.09	...	...	...	...	2
1.974								
1.973299	17.2	...	1.81 ± 0.27	...	...	...	...	1
1.973547	17.6	...	2.53 ± 0.28	...	...	...	...	2
1.974406	28.6	...	1.82 ± 0.29	...	...	...	...	3
1.974843	11.5	...	10.9 ± 0.2	...	...	...	...	4
1.975128	11.0	...	3.11 ± 0.17	...	...	...	...	5
2.090 ^a								
2.089562	15.4	...	2.90 ± 0.28	...	...	...	...	1
2.089756	4.7	...	0.88 ± 0.18	...	...	...	...	2
2.090285	5.4	...	0.63 ± 0.18	...	...	...	...	3
2.090856	7.6	...	1.26 ± 0.21	...	...	...	...	4
2.091048	8.6	...	11.0 ± 0.3	...	...	...	...	5
2.157								
2.156817	11.4	...	5.43 ± 0.23	...	...	...	...	1
2.156911	7.3	...	2.44 ± 0.18	...	...	...	...	2
2.330								
2.328970	39.3	(39.0)	5.42 ± 0.42	5.68 ± 1.76	...	...	...	1
2.329049	9.2	(7.6)	1.60 ± 0.21	< 0.82	...	...	...	2
2.329390	3.8	(3.0)	0.69 ± 0.12	0.71 ± 0.50	...	...	...	3
2.329668	15.4	(14.4)	1.15 ± 0.20	3.46 ± 0.84	...	...	...	4
2.329941	10.0	(8.3)	13.4 ± 0.2	4.47 ± 0.72	...	...	...	5
2.330100	8.9	(7.2)	11.4 ± 0.3	3.13 ± 0.68	...	...	...	6
2.330248	7.3	5.7	10.1 ± 0.3	13.5 ± 0.8	...	...	...	7
2.330420	25.8	(25.2)	24.5 ± 0.6	9.78 ± 1.83	...	...	...	8
2.330533	6.6	5.2	14.3 ± 0.3	4.14 ± 0.81	...	...	...	9
2.410 ^b								
2.409441	9.7	(8.0)	5.37 ± 0.26	< 0.67	< 0.23	...	...	1
2.410556	27.7	(27.2)	4.99 ± 0.39	< 1.38	< 0.45	...	...	2
2.410997	11.1	(9.6)	3.21 ± 0.26	< 1.04	< 0.31	...	...	3
2.438 ^c								
2.436407	(11)	(10.0)	< 0.45	4.97 ± 1.96	< 1.14	4.11 ± 1.47	...	1
2.436487	10.0	(8.3)	< 0.69	4.72 ± 2.30	33.1 ± 1.9	55.8 ± 2.9	...	2
2.436570	5.8	(4.7)	< 0.29	5.53 ± 1.31	50.2 ± 2.1	99.4 ± 3.6	...	3
2.436678	6.4	(5.2)	0.31 ± 0.19	3.75 ± 0.94	21.7 ± 0.9	45.1 ± 1.7	...	4
2.436858	14.0	(12.9)	0.62 ± 0.26	6.47 ± 1.34	6.78 ± 0.57	12.2 ± 1.8	...	5
2.437026	7.5	(6.1)	< 0.28	< 1.30	20.3 ± 0.6	32.6 ± 1.3	...	6
2.437178	14.3	(13.2)	0.55 ± 0.28	< 1.91	3.25 ± 0.57	...	...	7
2.437357	5.7	(4.5)	0.34 ± 0.17	1.23 ± 0.75	10.5 ± 0.4	16.2 ± 1.1	...	8
2.437588	7.4	(6.4)	1.52 ± 0.24	12.8 ± 1.2	13.5 ± 0.5	18.5 ± 1.3	...	9
2.437716	9.9	(8.3)	16.9 ± 0.4	94.6 ± 2.8	16.0 ± 0.6	13.4 ± 1.8	...	10
2.437922	10.7	(9.2)	38.6 ± 0.5	136 ± 4	27.4 ± 0.7	19.5 ± 2.4	...	11
2.438059	5.2	(4.1)	3.45 ± 0.50	40.7 ± 2.7	12.2 ± 1.2	...	...	12
2.438110	5.1	(4.1)	8.94 ± 0.47	31.2 ± 2.0	30.2 ± 1.7	62.7 ± 3.3	...	13
2.438221	4.6	(3.6)	5.51 ± 0.28	48.0 ± 1.8	67.4 ± 3.0	119 ± 4	...	14
2.438373	11.7	(10.4)	20.5 ± 0.5	36.9 ± 1.4	12.9 ± 0.6	13.9 ± 2.8	...	15
2.438535	4.8	(3.9)	4.03 ± 0.64	61.9 ± 2.8	6.26 ± 0.62	10.4 ± 1.0	...	16
2.438675	19.8	(19.1)	84.9 ± 2.8	64.0 ± 3.6	18.1 ± 1.6	17.7 ± 2.3	...	17
2.438728	3.3	(2.2)	1.16 ± 0.85	5.68 ± 1.38	6.03 ± 0.68	10.0 ± 1.2	...	18
2.438833	4.6	(3.6)	...	151 ± 13	25.5 ± 1.0	44.2 ± 2.0	...	19
2.438906	7.2	(5.6)	...	100 ± 7	7.43 ± 1.05	7.92 ± 1.13	...	20
2.439079	13.6	(12.5)	...	215 ± 8	2.25 ± 1.45	...	...	21
2.439098	3.3	(2.2)	...	< 3.24	5.09 ± 0.69	8.62 ± 1.08	...	22
2.439173	4.3	(3.2)	...	29.4 ± 2.9	2.68 ± 0.48	...	...	23
2.439283	4.3	(3.2)	74.3 ± 19.5	134 ± 13	10.0 ± 1.5	23.1 ± 2.3	...	24

TABLE 3—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.439372	11.3	(9.9)	< 18.00	< 23.90	12.5 ± 5.6	10.7 ± 5.3	...	25
2.439420	9.7	(8.0)	92.1 ± 14.2	201 ± 16	14.5 ± 4.9	12.2 ± 6.3	...	26
2.439482	16.5	(15.6)	49.3 ± 3.6	16.0 ± 5.7	17.4 ± 2.5	16.3 ± 8.2	...	27
2.439550	5.0	(4.0)	8.64 ± 1.36	17.3 ± 2.4	17.3 ± 1.1	38.6 ± 3.1	...	28
2.439823	9.7	(8.1)	37.8 ± 0.8	32.9 ± 1.3	< 0.29	...	...	29
2.439998	12.8	(11.5)	44.0 ± 1.0	13.5 ± 1.6	1.09 ± 0.47	...	...	30
2.440086	5.2	(4.1)	10.5 ± 0.6	15.4 ± 1.2	< 0.34	...	...	31
2.440252	14.1	(13.0)	4.91 ± 0.39	< 1.47	< 0.40	...	...	32
2.468 ^d								
2.465518	9.8	(8.2)	0.82 ± 0.21	< 0.94	< 0.30	...	...	1
2.466079	13.7	(12.5)	2.64 ± 0.27	1.58 ± 0.87	< 0.34	...	...	2
2.467037	8.4	(7.1)	3.54 ± 0.27	12.8 ± 0.7	...	...	...	3
2.467190	9.5	(7.7)	3.80 ± 0.34	5.06 ± 0.70	...	...	...	4
2.467409	12.0	(10.7)	12.0 ± 0.4	36.8 ± 0.9	5.37 ± 0.36	...	...	5
2.467755	15.2	(14.2)	7.90 ± 0.40	6.71 ± 0.84	0.78 ± 0.36	...	...	6
2.468117	18.5	(17.7)	3.68 ± 0.42	2.15 ± 0.91	< 0.37	...	...	7
2.468760	10.0	(8.4)	1.03 ± 0.31	1.64 ± 0.74	0.47 ± 0.30	...	...	8
2.469769	13.8	(12.7)	0.59 ± 0.27	< 1.14	< 0.45	...	...	9
2.474 ^e								
2.473032	6.3	(5.1)	0.85 ± 0.18	2.35 ± 0.55	< 0.28	...	...	1
2.473651	11.6	(10.2)	39.3 ± 0.5	17.3 ± 0.8	1.06 ± 0.38	...	5.39 ± 0.39	2
2.473833	8.9	(7.3)	23.3 ± 0.4	13.9 ± 0.7	0.88 ± 0.35	...	0.86 ± 0.32	3
2.474193	5.2	(3.8)	36.2 ± 0.5	58.8 ± 1.1	11.7 ± 0.3	6.91 ± 1.82	1.17 ± 0.26	4
2.474560	6.3	(5.1)	4.30 ± 0.30	1.32 ± 0.84	< 0.48	...	...	5
2.474597	20.0	(19.2)	11.8 ± 0.4	8.59 ± 1.46	< 1.17	...	...	6
2.484 ^f								
2.483641	5.3	(4.8)	5.58 ± 0.16	2.18 ± 1.07	< 0.26	...	...	1
2.502 ^g								
2.501575	3.8	(3.0)	0.58 ± 0.14	< 0.74	...	...	...	1
2.501685	59.3	(59.1)	4.15 ± 0.46	< 1.92	...	...	...	2
2.502266	10.7	(9.2)	8.62 ± 0.22	< 0.69	...	...	...	3
2.502459	4.4	(3.7)	0.74 ± 0.14	< 0.49	< 0.30	...	...	4
2.555 ^h								
2.554824	8.9	(7.1)	2.24 ± 0.14	< 2.53	...	...	...	1
2.555470	24.8	(24.2)	4.31 ± 0.22	< 1.60	...	...	...	2
2.616 ⁱ								
2.614806	5.7	(4.8)	1.30 ± 0.12	< 0.49	...	< 0.25	< 0.37	1
2.615306	6.8	4.8	16.4 ± 0.3	15.0 ± 0.6	...	< 0.26	< 0.42	2
2.615599	10.4	(10.1)	1.12 ± 0.15	< 0.66	...	< 0.33	< 0.34	3
2.615859	10.1	(8.5)	3.16 ± 0.16	< 0.69	...	< 0.31	0.47 ± 0.18	4
2.616065	6.9	(5.8)	7.44 ± 0.18	< 0.71	...	< 0.32	< 0.24	5
2.616292	9.9	(8.3)	4.23 ± 0.16	< 0.63	...	< 0.34	< 0.20	6
2.616516	8.4	(6.9)	2.74 ± 0.15	1.35 ± 0.57	< 0.49	< 0.31	< 0.18	7
2.616812	3.7	(2.4)	0.42 ± 0.10	< 0.43	< 0.25	< 0.29	< 0.13	8
2.617053	8.8	(7.3)	9.57 ± 0.20	< 0.58	< 0.70	< 0.29	0.87 ± 0.17	9
2.617345	7.5	(6.5)	0.45 ± 0.13	< 0.59	< 0.86	< 0.28	< 0.21	10
2.617572	4.9	(4.1)	5.28 ± 0.18	< 0.50	< 0.28	< 0.25	1.08 ± 0.19	11
2.617702	4.2	(3.2)	1.43 ± 0.20	< 0.57	< 0.32	< 0.28	0.76 ± 0.22	12
2.617803	19.0	(18.2)	23.0 ± 0.4	...	< 0.62	< 0.60	1.85 ± 0.41	13
2.618136	4.2	3.1	7.83 ± 0.20	7.96 ± 0.53	0.80 ± 0.26	0.81 ± 0.23	< 0.41	14
2.623 ^j								
2.622674	3.7	(2.4)	0.57 ± 0.12	< 0.47	...	< 0.45	< 0.17	1
2.623208	11.9	(10.6)	4.99 ± 0.20	< 0.79	< 0.51	< 0.33	< 0.35	2
2.623486	11.5	(10.1)	4.15 ± 0.21	3.23 ± 0.78	0.91 ± 0.38	0.73 ± 0.33	0.39 ± 0.22	3

*See Figure 1.

^aC IV $\lambda 1551$ is immersed in Si IV $\lambda 1394$ at $z = 2.438$ but $\lambda 1548$ is clear.^bC IV $\lambda 1551$ in component 1 is contaminated but $\lambda 1548$ is clear. Si IV $\lambda 1403$ is masked by C IV $\lambda 1548$ at $z = 2.090$ and the upper limit values come from $\lambda 1394$. C II is outside the forest.

^cThis is highly complex system with components 3 and 14 particularly strong in C II and Si II and relatively weak in C IV: in these, respective values $\log N(\text{H I}) \sim 19.7$ and ~ 19.5 give a good fit to the H I Lyman α damping wings. Overall C IV is also very strong and in components 19–23 $\lambda\lambda 1548, 1551$ both are too saturated to be useful; here C II provides the values for $b(\text{C})$. Si IV $\lambda 1394$ contains C IV $\lambda 1551$ at $z = 2.090$ but $\lambda 1403$ is clear and good values are obtained throughout. Si II $\lambda 1260$, in the forest but only mildly contaminated, is used to supplement $\lambda\lambda 1304, 1527$ and all are collectively self-consistent; errors are from $\lambda\lambda 1304, 1527$.

^dC IV $\lambda 1551$ is partially blended with C IV $\lambda 1548$ at $z = 2.474$ but $\lambda 1548$ is clear. In C II apparent contamination of components 3 and 4 makes these values too uncertain to include.

^eC IV $\lambda 1548$ is partially blended with C IV $\lambda 1551$ at $z = 2.468$ but $\lambda 1551$ is clear. The Si II value is from $\lambda 1527$. N V is in the forest but for components 2–4 useful values come from $\lambda 1239$, in a relatively clear region, which show velocity structure corresponding to these components in C IV.

^fSi IV $\lambda 1394$ is contaminated and the upper limit comes from $\lambda 1403$.

^gC II in components 1–3 is masked by Mg II $\lambda 2804$ at $z = 0.667$.

^hC II is very weak and too noisy to give useful upper limits. Si II $\lambda 1260$ is outside the forest but masked by N V $\lambda 1239$ at $z = 2.616$.

ⁱC IV $\lambda 1551$ is blended with weaker C IV $\lambda 1548$ at $z = 2.623$ but $\lambda 1548$ is clear. C II in components 1–6 is masked by Si IV $\lambda 1403$ at $z = 2.438$. Si II $\lambda 1260$ is outside the forest. N V is outside the forest; in components 1–3 $\lambda 1239$ is blended with O I $\lambda 1302$ at $z = 2.438$, and in component 14 with Si II $\lambda 1304$ in the same system and only $\lambda 1243$ is used for these upper limits.

^jC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 2.616$ but $\lambda 1551$ is clear. In C II the close proximity to Si IV $\lambda 1393$ at $z = 2.468$ makes component 1 too uncertain to use.

TABLE 4
HEAVY ELEMENT ABSORPTION LINES: Q1107+4847 $z_{em} = 2.97^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.117								
2.117248	17.1	...	2.24 ± 0.11	...	...	...	...	1
2.142								
2.141490	6.4	...	0.54 ± 0.10	...	...	...	...	1
2.143								
2.143093	4.6	...	2.23 ± 0.12	...	...	...	...	1
2.143184	6.3	...	14.2 ± 0.2	...	...	...	...	2
2.143335	7.8	...	2.33 ± 0.12	...	...	...	...	3
2.153								
2.153335	4.5	...	0.80 ± 0.08	...	...	...	...	1
2.153493	9.5	...	2.78 ± 0.11	...	...	...	...	2
2.662 ^a								
2.661835	9.2	(7.4)	3.36 ± 0.15	1.04 ± 0.72	< 0.23	...	...	1
2.662468	7.4	(5.9)	1.43 ± 0.17	< 0.62	< 0.17	...	...	2
2.685								
2.684123	3.7	(2.4)	0.53 ± 0.19	1.46 ± 0.71	< 0.22	...	...	1
2.684549	5.5	(4.5)	2.78 ± 0.80	9.10 ± 1.54	< 0.35	...	...	2
2.684715	10.9	(9.4)	1.42 ± 0.87	< 2.32	< 0.63	...	...	3
2.696								
2.695956	43.6	(43.2)	5.04 ± 0.57	< 2.00	< 0.71	...	...	1
2.696317	23.6	(23.0)	2.71 ± 0.43	< 1.52	< 0.54	...	...	2
2.696644	7.8	(6.3)	5.02 ± 0.20	1.95 ± 0.67	< 0.76	...	...	3
2.696901	4.9	(4.2)	0.92 ± 0.14	1.26 ± 0.58	< 0.21	...	...	4
2.724 ^b								
2.722186	6.0	(4.9)	9.77 ± 0.19	1.53 ± 0.64	< 0.24	...	...	1
2.723566	9.8	(8.2)	0.88 ± 0.17	0.91 ± 0.70	...	...	...	2
2.723861	8.2	(6.8)	4.15 ± 0.17	11.3 ± 0.7	0.44 ± 0.27	...	...	3
2.724090	5.2	(4.3)	3.06 ± 0.27	29.4 ± 1.5	1.01 ± 0.37	0.74 ± 0.41	...	4
2.724189	14.9	(13.9)	14.2 ± 0.5	55.2 ± 2.2	4.30 ± 0.68	4.19 ± 0.73	...	5
2.724466	16.6	(15.6)	9.61 ± 0.54	11.2 ± 2.3	< 0.87	...	...	6
2.724542	6.1	(5.0)	4.34 ± 0.33	8.01 ± 1.34	< 0.58	...	...	7
2.724852	13.2	(12.0)	1.33 ± 0.21	7.72 ± 1.04	1.76 ± 0.36	...	...	8
2.725055	6.0	(4.9)	0.50 ± 0.15	6.75 ± 0.77	1.01 ± 0.26	...	...	9
2.761 ^c								
2.758802	12.2	(10.9)	1.05 ± 0.22	< 0.89	< 0.52	...	...	1
2.759076	7.3	(6.0)	52.9 ± 1.2	23.2 ± 1.0	0.88 ± 0.27	...	4.64 ± 0.44	2
2.759297	9.8	(8.1)	425 ± 32	193 ± 4	10.7 ± 0.4	6.02 ± 2.32	11.9 ± 0.6	3
2.759444	3.6	(2.7)	7.36 ± 3.53	83.1 ± 4.6	7.55 ± 0.34	10.7 ± 1.8	...	4
2.759587	19.6	(18.8)	6.30 ± 0.39	< 1.38	< 0.39	...	...	5
2.759974	4.8	(4.0)	3.95 ± 0.18	< 0.63	< 0.22	...	...	6
2.760197	10.4	(8.9)	3.87 ± 0.29	< 1.48	< 0.39	...	...	7
2.760287	4.4	(3.7)	14.4 ± 0.4	< 0.78	< 0.29	...	5.54 ± 0.51	8
2.760492	10.3	(8.8)	7.97 ± 0.26	< 1.18	< 0.48	...	...	9
2.760643	4.5	(3.9)	7.41 ± 0.27	9.75 ± 0.77	< 0.23	...	...	10
2.760785	7.9	(6.3)	20.1 ± 0.3	13.2 ± 0.8	0.93 ± 0.28	...	...	11
2.760985	6.8	(5.7)	18.5 ± 0.5	13.0 ± 0.8	0.57 ± 0.27	...	...	12
2.761139	8.4	(6.6)	64.2 ± 1.2	27.5 ± 1.0	2.29 ± 0.33	...	...	13
2.761307	7.8	(6.6)	10.1 ± 0.6	16.2 ± 1.1	0.82 ± 0.36	...	...	14
2.761430	7.2	(5.4)	43.6 ± 0.9	69.5 ± 1.7	9.65 ± 0.39	9.42 ± 2.08	...	15
2.761591	10.6	(9.0)	7.66 ± 0.29	14.3 ± 1.0	< 0.37	...	...	16
2.761831	7.5	(6.2)	3.68 ± 0.20	17.8 ± 0.9	7.40 ± 0.31	6.90 ± 2.01	...	17
2.761996	7.0	(5.7)	5.53 ± 0.23	20.7 ± 0.9	4.51 ± 0.32	3.33 ± 1.95	...	18
2.762142	6.7	(5.4)	5.66 ± 0.31	14.1 ± 0.9	5.57 ± 0.44	9.86 ± 2.31	...	19
2.762315	9.7	(8.1)	20.8 ± 1.0	46.0 ± 2.1	70.4 ± 1.4	106 ± 5	...	20
2.762392	4.9	(4.1)	224 ± 17	234 ± 15	< 1.17	< 3.77	...	21
2.762516	3.3	(2.5)	6.97 ± 0.45	9.51 ± 1.03	7.57 ± 0.39	...	...	22
2.762624	15.0	(14.0)	7.58 ± 0.33	17.8 ± 1.3	7.92 ± 0.49	...	...	23

TABLE 4—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.762901	4.8	(4.4)	3.56 ± 0.24	18.9 ± 1.2	2.69 ± 0.32	4.65 ± 2.83	...	24
2.762995	4.6	(3.8)	3.26 ± 0.28	20.6 ± 1.3	12.6 ± 0.5	28.9 ± 3.2	...	25
2.763076	4.8	(4.0)	9.34 ± 0.31	21.3 ± 1.1	< 0.35	...	...	26
2.763246	11.4	(10.0)	3.67 ± 0.31	7.32 ± 1.20	3.72 ± 0.48	...	...	27
2.763334	3.3	(2.4)	1.04 ± 0.20	8.65 ± 0.91	8.02 ± 0.39	19.1 ± 2.9	...	28
2.763478	6.5	(5.2)	1.91 ± 0.18	6.64 ± 0.74	9.11 ± 0.32	9.25 ± 2.52	...	29
2.763659	10.6	(10.4)	0.70 ± 0.20	3.22 ± 0.90	3.97 ± 0.33	...	...	30
2.763976	8.2	(6.7)	< 0.27	1.80 ± 0.72	9.51 ± 0.31	15.0 ± 2.4	...	31
2.870 ^d								
2.869957	11.3	(9.9)	3.37 ± 0.26	< 2.25	...	< 0.48	...	1
2.870287	10.9	(9.4)	12.4 ± 0.3	31.7 ± 2.3	< 0.38	< 0.60	...	2
2.870562	13.2	(12.0)	5.29 ± 0.31	< 2.54	< 0.41	< 0.28	...	3
2.909 ^e								
2.908768	10.1	...	2.17 ± 0.16	...	...	...	< 0.18	1
2.956 ^f								
2.956154	11.4	(10.0)	1.14 ± 0.15	< 0.72	...	< 0.53	< 0.28	1

*See Figure 1.

^aSi IV $\lambda 1403$ in component 1 appears contaminated and is not used but $\lambda 1394$ is clear. C II is outside the forest.

^bSi IV $\lambda 1403$ in components 1–4 is blended with Mg II $\lambda 2804$ at $z = 0.863$ but $\lambda 1394$ is clear. C II in component 2 is too noisy to be useful. Si II $\lambda 1260$ is in the forest but is used together with weak $\lambda 1527$ and consistent values are obtained for components 4 and 5.

^cThis is a highly complex system. Component 20 has strong C II and Si II but C IV is not unusually weak in comparison; for this $\log N(\text{H I}) \sim 19.1$ gives a good fit to the outer parts of the associated H I Lyman α damping wings. The adjoining component 21 is very strong in C IV and Si IV but undetectable in the low ionization species. Si II $\lambda 1260$ is in the forest but this and $\lambda 1193$ are used to supplement $\lambda 1527$ and available portions of $\lambda 1304$: the values obtained for the stronger components are listed with errors from $\lambda\lambda 1304, 1527$. N V is in the forest but good values for components 2, 3 and 8 come from both members of the doublet.

^dSi IV $\lambda 1394$ is not used because the feature at this position is too strong relative to $\lambda 1403$. Si II $\lambda 1260$ is outside the forest.

^eSi IV $\lambda 1393$ coincides with Al III $\lambda 1855$ at $z = 1.938$ and $\lambda 1403$ is too noisy to give a reliable value. C II and Si II both are too contaminated to be useful. N V is outside the forest.

^fThis is close to z_{em} . C II, which here would yield only an upper limit, is masked by Si IV $\lambda 1403$ at $z = 2.761$.

TABLE 5
HEAVY ELEMENT ABSORPTION LINES: Q0636+6801 $z_{em} = 3.18^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.311								
2.310144	9.4	...	2.65 ± 0.16	...	...	...	...	1
2.310436	8.4	...	3.10 ± 0.16	...	...	...	...	2
2.310659	8.3	...	3.24 ± 0.16	...	...	...	...	3
2.311034	16.4	...	20.1 ± 0.3	...	...	...	...	4
2.311266	12.1	...	15.3 ± 0.2	...	...	...	...	5
2.311701	22.4	...	9.06 ± 0.27	...	...	...	...	6
2.312124	9.6	...	0.83 ± 0.16	...	...	...	...	7
2.312480	25.7	...	3.94 ± 0.29	...	...	...	...	8
2.325								
2.324375	4.4	...	0.25 ± 0.08	...	...	...	...	1
2.324733	9.3	...	2.13 ± 0.12	...	...	...	...	2
2.324870	7.1	...	4.49 ± 0.12	...	...	...	...	3
2.325083	11.0	...	3.37 ± 0.13	...	...	...	...	4
2.325250	6.8	...	0.26 ± 0.10	...	...	...	...	5
2.436								
2.435488	3.2	...	0.69 ± 0.09	...	...	...	...	1
2.474 ^a								
2.472728	4.8	...	11.1 ± 0.3	...	...	...	...	1
2.472757	13.4	...	5.75 ± 0.38	...	...	...	...	2
2.473157	8.0	...	5.84 ± 0.17	...	...	...	...	3
2.473406	5.8	...	3.64 ± 0.15	...	...	...	...	4
2.473570	9.8	...	5.79 ± 0.18	...	...	...	...	5
2.473849	19.4	...	5.74 ± 0.25	...	...	...	...	6
2.474483	7.0	...	13.0 ± 0.2	...	...	...	...	7
2.474607	10.7	...	8.13 ± 0.22	...	...	...	...	8
2.474945	15.2	...	11.0 ± 0.2	...	...	...	...	9
2.475229	6.8	(5.7)	53.4 ± 0.7	77.6 ± 4.4	2.69 ± 0.47	3.07 ± 0.78	...	10
2.475353	5.6	3.8	56.1 ± 1.1	113 ± 7	11.0 ± 0.6	10.8 ± 0.9	...	11
2.475462	9.1	...	17.2 ± 0.3	...	...	...	...	12
2.475853	28.9	...	5.96 ± 0.40	...	...	...	...	13
2.475952	7.0	...	3.29 ± 0.18	...	...	...	...	14
2.595								
2.594488	8.2	...	1.86 ± 0.12	...	...	...	...	1
2.594723	4.6	...	0.79 ± 0.11	...	...	...	...	2
2.594813	5.8	...	1.46 ± 0.12	...	...	...	...	3
2.621								
2.620991	12.6	...	1.69 ± 0.23	...	...	...	...	1
2.621408	17.2	...	4.90 ± 0.27	...	...	...	...	2
2.681 ^b								
2.680206	8.7	(6.9)	1.49 ± 0.19	< 0.94	...	...	...	1
2.681560	16.8	(15.9)	0.94 ± 0.31	< 1.62	...	...	...	2
2.681707	8.0	(6.3)	0.49 ± 0.22	1.43 ± 1.11	...	...	...	3
2.682112	16.9	(15.9)	6.59 ± 0.26	< 1.33	...	...	...	4
2.690								
2.690462	7.6	(6.3)	1.67 ± 0.21	1.38 ± 0.44	...	...	...	1
2.868 ^c								
2.867163	9.3	(7.5)	0.35 ± 0.20	< 1.14	< 0.32	...	...	1
2.867425	6.5	(5.3)	0.97 ± 0.18	< 1.02	< 0.19	...	...	2
2.867898	9.4	(7.6)	3.48 ± 0.22	< 0.86	< 0.26	...	...	3
2.868403	8.6	(6.8)	0.83 ± 0.18	< 0.57	< 0.21	...	...	4
2.868776	9.1	(7.3)	5.30 ± 0.21	3.08 ± 0.55	< 0.21	...	...	5
2.892								
2.890399	6.4	(5.2)	0.81 ± 0.12	1.05 ± 0.46	< 0.24	...	...	1
2.890728	14.6	(13.5)	1.18 ± 0.19	< 1.00	< 0.35	...	...	2
2.890956	3.7	(2.4)	0.43 ± 0.11	< 0.49	< 0.33	...	...	3
2.891170	3.7	(2.4)	0.79 ± 0.11	< 0.38	< 0.20	...	...	4
2.891325	7.3	(6.0)	3.44 ± 0.14	< 0.52	< 0.26	...	...	5
2.891551	11.1	(9.6)	1.18 ± 0.16	2.05 ± 0.61	0.71 ± 0.30	...	...	6
2.891850	6.5	(5.7)	7.40 ± 0.21	1.29 ± 0.61	< 0.50	...	...	7
2.891949	22.7	(22.0)	11.0 ± 0.4	< 1.22	< 0.62	...	...	8

TABLE 5—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.893129	11.2	(9.8)	2.38 ± 0.16	< 0.67	< 0.40	...	...	9
2.893908	3.7	(2.4)	0.44 ± 0.10	< 0.43	< 0.32	...	...	10
2.904 ^d								
2.902425	20.3	...	7.52 ± 0.31	...	...	...	...	1
2.902592	8.2	(6.8)	4.42 ± 0.28	16.7 ± 1.0	< 0.58	...	...	2
2.902788	16.0	(15.1)	21.8 ± 0.7	61.2 ± 2.3	< 0.90	...	...	3
2.902947	25.5	(24.9)	28.5 ± 0.9	20.2 ± 2.9	4.14 ± 1.21	...	...	4
2.903233	4.3	(3.3)	1.46 ± 0.24	7.27 ± 0.84	< 0.43	...	...	5
2.903325	20.2	(19.5)	28.7 ± 0.5	52.0 ± 1.8	2.20 ± 0.77	...	...	6
2.903622	7.1	(5.8)	1.91 ± 0.18	< 0.67	< 0.56	...	...	7
2.903881	7.3	(6.3)	2.05 ± 0.41	28.1 ± 1.4	1.81 ± 1.20	...	...	8
2.903969	15.8	(14.8)	18.8 ± 0.7	12.3 ± 2.1	< 2.37	...	...	9
2.904118	3.8	(2.9)	5.56 ± 0.32	34.9 ± 1.5	$[486 \pm 57]$	524 ± 12	...	10
2.904254	7.0	(5.8)	31.5 ± 0.6	330 ± 8	79.1 ± 13.5	167 ± 5	...	11
2.904380	7.7	(6.3)	4.38 ± 1.30	160 ± 8	213 ± 31	492 ± 7	...	12
2.904546	18.4	(17.5)	94.6 ± 3.5	432 ± 14	35.2 ± 17.6	17.4 ± 7.4	...	13
2.904656	9.2	(7.4)	24.4 ± 3.5	182 ± 17	< 16.10	37.3 ± 7.2	...	14
2.904704	5.6	(4.6)	< 1.79	40.5 ± 8.9	117 ± 8	182 ± 6	...	15
2.904924	5.7	(4.7)	3.31 ± 0.55	7.83 ± 1.90	2.35 ± 1.13	5.14 ± 1.26	...	16
2.904928	25.6	(25.0)	16.3 ± 1.6	65.2 ± 5.8	< 3.54	...	...	17
2.905130	6.4	4.6	9.26 ± 0.44	75.9 ± 2.0	12.8 ± 1.0	15.7 ± 1.1	...	18
2.905290	9.3	(7.6)	3.27 ± 0.25	20.8 ± 1.1	4.14 ± 0.55	8.57 ± 0.85	...	19
2.905463	4.7	2.7	< 0.26	1.77 ± 0.77	5.71 ± 0.47	13.8 ± 1.0	...	20
2.905486	19.3	(18.5)	3.27 ± 0.40	16.1 ± 1.8	2.03 ± 0.92	...	...	21
3.009								
3.007389	8.7	(6.8)	1.02 ± 0.25	< 0.57	< 0.39	...	...	1
3.010072	13.3	(12.1)	4.65 ± 0.31	< 0.67	< 0.49	...	...	2
3.013								
3.012866	17.5	(16.6)	0.83 ± 0.34	< 0.77	< 0.49	...	...	1
3.013227	18.5	(17.6)	2.33 ± 0.43	< 0.91	< 0.61	...	...	2
3.013444	12.7	(11.5)	9.83 ± 0.38	5.91 ± 0.73	< 0.53	...	...	3
3.013706	3.2	(2.5)	0.82 ± 0.17	< 0.36	< 0.26	...	...	4
3.013909	9.3	(7.5)	1.95 ± 0.24	< 0.49	< 0.34	...	...	5
3.018								
3.017206	6.2	(5.4)	22.1 ± 0.4	5.71 ± 0.58	0.40 ± 0.31	...	...	1
3.017367	6.4	(5.2)	18.0 ± 0.4	2.96 ± 0.57	< 0.37	...	...	2
3.017513	7.5	(5.1)	3.51 ± 0.26	< 0.62	< 0.34	...	...	3
3.017851	2.6	(1.7)	0.79 ± 0.23	< 0.44	< 0.24	...	...	4
3.111 ^e								
3.111291	10.3	(8.7)	2.34 ± 0.15	< 0.52	< 0.76	< 0.22	< 0.54	1

*See Figure 1.

^aIn the strong, narrow components 10 and 11 Si IV $\lambda 1394$, C II and Si II $\lambda 1260$, all in the forest, are relatively free of contamination and well-measured; additionally Si II $\lambda 1527$, outside the forest, is used to supplement $\lambda 1260$ in these components but elsewhere is too weak to give useful values.

^bSi IV $\lambda 1394$ is blended with C IV $\lambda 1548$ at $z = 2.311$ and overall is rather noisy, but $\lambda 1403$ is clear.

^cSi IV $\lambda 1394$ in components 1 and 2 is blended with stronger C IV $\lambda 1551$ at $z = 2.474$ but $\lambda 1403$ is clear. C II is outside the forest.

^dThis is a highly complex system with strong C II and Si II and relatively weak C IV in components 10, 12 and 15: From the extent of the H I Lyman α wings associated with these the limit on the combined column densities is $\log N(\text{H I}) \lesssim 18.7$. In the broad component 1 Si IV and C II are weak and too uncertain to include. C II in component 10 is close to saturation and the value (in square brackets) is approximate only. Si II $\lambda 1260$ is in the forest but onward from component 10 is relatively clear of contamination and is used together with $\lambda 1304$ which is outside and relatively strong except in components 1–9 (upper limits from the latter are too high to be useful). For component 20 $b(\text{C})$ comes from C II.

^eSi II $\lambda 1260$ is outside the forest. N V is outside the forest; $\lambda 1239$ is blended with strong Si II $\lambda 1304$ at $z = 2.904$ and the upper limit is from $\lambda 1243$.

TABLE 6
HEAVY ELEMENT ABSORPTION LINES: Q1425+6039 $z_{em} = 3.18^*$

z	$b(C)$ km s^{-1}	$b(Si)$ km s^{-1}	$N(C\text{ IV})$ 10^{12}cm^{-2}	$N(Si\text{ IV})$ 10^{11}cm^{-2}	$N(C\text{ II})$ 10^{12}cm^{-2}	$N(Si\text{ II})$ 10^{11}cm^{-2}	$N(N\text{ V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.343								
2.342638	9.9	...	4.83 ± 0.07	...	...	...	...	1
2.342805	10.1	...	5.57 ± 0.07	...	...	...	...	2
2.343092	8.3	...	2.50 ± 0.06	...	...	...	...	3
2.476								
2.475425	13.2	...	2.16 ± 0.12	...	...	...	...	1
2.475714	12.9	...	4.87 ± 0.13	...	...	...	...	2
2.475989	7.4	...	8.01 ± 0.12	...	...	...	...	3
2.476169	3.9	...	0.38 ± 0.08	...	...	...	...	4
2.476537	2.1	...	0.24 ± 0.07	...	...	...	...	5
2.486								
2.485329	11.7	...	2.04 ± 0.10	...	...	...	...	1
2.485620	10.4	...	4.17 ± 0.10	...	...	...	...	2
2.486001	8.1	...	2.27 ± 0.09	...	...	...	...	3
2.486212	9.9	...	7.76 ± 0.11	...	...	...	...	4
2.486445	10.6	...	10.5 ± 0.1	...	...	...	...	5
2.486614	7.8	...	9.60 ± 0.12	...	...	...	...	6
2.486826	10.4	...	18.8 ± 0.2	...	...	...	...	7
2.487025	12.9	...	12.6 ± 0.2	...	...	...	...	8
2.487356	29.2	...	0.99 ± 0.17	...	...	...	...	9
2.513								
2.513429	8.3	...	1.29 ± 0.11	...	...	...	...	1
2.606								
2.605723	7.4	...	1.13 ± 0.08	...	...	...	...	1
2.624								
2.624426	16.3	...	1.77 ± 0.16	...	...	...	...	1
2.646 ^a								
2.645649	12.5	(11.2)	1.13 ± 0.11	< 0.58	...	...	...	1
2.646243	23.5	(22.8)	1.03 ± 0.16	< 1.52	...	...	...	2
2.646535	11.8	(10.4)	4.08 ± 0.12	< 0.61	...	...	...	3
2.702 ^b								
2.702156	20.9	(20.1)	0.99 ± 0.14	< 0.51	...	...	...	1
2.702441	8.0	(6.6)	0.69 ± 0.09	0.75 ± 0.24	...	...	...	2
2.726 ^c								
2.726061	24.1	(23.5)	2.98 ± 0.17	< 0.75	...	...	...	1
2.726257	11.1	(9.7)	3.07 ± 0.12	3.71 ± 0.37	...	...	...	2
2.770 ^d								
2.768764	14.6	(13.6)	0.70 ± 0.12	1.82 ± 0.40	...	< 1.45	...	1
2.769092	8.4	(6.9)	2.44 ± 0.10	0.89 ± 0.29	...	< 1.18	...	2
2.769310	7.3	(6.1)	0.66 ± 0.09	5.28 ± 0.30	...	2.76 ± 1.21	...	3
2.769581	16.9	(15.9)	4.45 ± 0.16	2.24 ± 0.50	...	10.1 ± 2.2	...	4
2.769745	5.6	(4.7)	2.13 ± 0.11	42.4 ± 0.5	...	608 ± 9	...	5
2.769848	3.3	(2.2)	0.57 ± 0.13	8.31 ± 0.43	...	548 ± 54	...	6
2.769925	7.2	(6.0)	1.67 ± 0.19	16.8 ± 0.6	...	459 ± 10	...	7
2.770007	3.7	(2.7)	0.39 ± 0.13	8.87 ± 0.43	...	275 ± 12	...	8
2.770100	6.0	(4.9)	0.94 ± 0.12	8.21 ± 0.38	...	192 ± 3	...	9
2.770230	30.1	(29.6)	1.62 ± 0.22	< 0.74	...	< 1.74	...	10
2.771032	6.9	(5.6)	0.91 ± 0.08	7.66 ± 0.30	...	3.21 ± 1.13	...	11
2.773 ^e								
2.772514	11.5	(10.1)	3.31 ± 0.25	< 0.31	...	...	...	1
2.772704	6.8	(3.9)	$[494 \pm 9]$	5.72 ± 0.27	0.88 ± 0.14	...	121 ± 2	2
2.772841	4.0	(2.7)	56.8 ± 1.6	3.53 ± 0.47	0.57 ± 0.15	...	11.1 ± 0.8	3
2.772871	9.6	(7.9)	2.72 ± 0.47	< 0.68	...	...	...	4
2.773405	24.0	(23.3)	2.86 ± 0.24	< 0.45	...	...	...	5
2.774060	15.6	(14.6)	1.14 ± 0.19	< 0.36	...	...	...	6
2.796								
2.795950	5.6	(4.7)	2.22 ± 0.12	< 0.39	...	...	...	1
2.796160	10.2	(8.6)	1.72 ± 0.14	< 0.44	...	...	...	2

TABLE 6—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.827^f								
2.825061	9.0	(7.1)	1.01 ± 0.12	1.29 ± 0.45	2.15 ± 0.14	2.04 ± 1.19	...	1
2.825309	7.6	(6.1)	2.12 ± 0.14	< 0.45	9.82 ± 0.20	12.6 ± 0.4	...	2
2.825426	4.2	(3.2)	25.2 ± 0.4	4.32 ± 0.59	20.1 ± 0.4	33.1 ± 1.0	...	3
2.825511	3.6	(2.5)	27.7 ± 0.7	16.5 ± 0.9	27.8 ± 0.8	8.53 ± 2.36	...	4
2.825598	5.5	(4.4)	18.5 ± 0.3	15.0 ± 0.9	82.5 ± 2.1	539 ± 67	...	5
2.825740	7.0	(5.7)	6.88 ± 0.72	7.23 ± 1.11	104 ± 5	166 ± 14	...	6
2.825808	(11)	9.5	< 1.94	25.0 ± 1.6	< 7.48	< 13.9	...	7
2.825894	5.8	(4.9)	2.44 ± 0.61	< 1.59	51.4 ± 3.5	97.7 ± 7.6	...	8
2.826001	13.8	(12.6)	26.4 ± 0.6	78.5 ± 1.6	46.5 ± 3.2	22.7 ± 2.4	...	9
2.826111	5.7	(5.7)	< 0.37	< 1.98	18.0 ± 7.1	52.1 ± 3.1	...	10
2.826217	9.6	(7.8)	5.74 ± 0.55	9.33 ± 1.63	99.6 ± 29.4	41.3 ± 6.2	...	11
2.826301	9.7	(8.0)	9.87 ± 0.49	26.8 ± 1.4	83.1 ± 68.3	238 ± 9	...	12
2.826444	5.2	(3.8)	3.16 ± 0.29	5.30 ± 0.77	...	348 ± 30	...	13
2.826544	7.7	(6.1)	7.23 ± 0.62	19.1 ± 1.9	...	...	...	14
2.826621	(11)	9.5	< 1.90	9.40 ± 5.82	...	...	...	15
2.826708	15.5	(14.5)	8.70 ± 1.98	32.7 ± 8.4	...	...	...	16
2.826794	22.1	(21.4)	40.0 ± 3.0	67.3 ± 9.5	...	...	...	17
2.826844	(13)	12.0	< 2.12	41.4 ± 6.2	...	...	...	18
2.827186	4.6	(3.7)	0.65 ± 0.35	< 1.03	183 ± 40	298 ± 12	...	19
2.827251	16.9	(16.0)	23.6 ± 1.1	41.3 ± 3.3	< 26.8	37.5 ± 14.7	...	20
2.827372	7.3	(6.0)	3.49 ± 0.48	12.8 ± 1.4	125 ± 8	201 ± 6	...	21
2.827548	14.2	(13.1)	3.26 ± 0.46	< 1.83	4.31 ± 2.94	23.9 ± 5.9	...	22
2.827623	8.1	(6.5)	< 0.38	3.94 ± 1.02	99.5 ± 1.8	178 ± 4	...	23
2.827797	9.3	(7.6)	1.71 ± 0.19	< 0.64	31.6 ± 0.5	54.5 ± 2.9	...	24
2.827953	12.9	(11.7)	5.12 ± 0.36	11.8 ± 1.3	0.78 ± 0.48	< 4.31	...	25
2.828063	16.4	(15.5)	2.67 ± 0.34	< 1.32	1.17 ± 0.40	...	...	26
2.830^g								
2.828528	13.7	(12.6)	2.44 ± 0.14	2.93 ± 0.49	0.29 ± 0.14	...	...	1
2.828808	11.0	(9.5)	2.45 ± 0.16	3.02 ± 0.55	1.99 ± 0.14	...	...	2
2.829030	3.3	(2.2)	< 0.13	0.57 ± 0.40	0.92 ± 0.11	...	...	3
2.829348	15.2	(14.2)	4.94 ± 1.14	32.8 ± 2.8	18.3 ± 0.8	27.0 ± 4.9	...	4
2.829359	3.3	(2.2)	1.42 ± 0.17	7.41 ± 0.64	5.28 ± 0.19	7.70 ± 1.56	...	5
2.829504	37.2	(36.8)	35.8 ± 2.4	< 5.73	< 1.62	...	...	6
2.829548	5.9	(4.8)	25.9 ± 0.6	51.8 ± 1.6	0.39 ± 0.20	...	...	7
2.829648	7.2	(5.8)	75.9 ± 3.8	168 ± 3	20.4 ± 0.4	22.7 ± 2.0	...	8
2.829749	5.2	(4.2)	12.7 ± 1.4	93.7 ± 3.6	18.0 ± 0.4	27.9 ± 2.1	...	9
2.829807	8.1	(6.7)	44.7 ± 1.1	66.9 ± 2.3	3.24 ± 0.47	< 2.97	...	10
2.829898	14.3	(13.2)	1.34 ± 0.61	11.9 ± 1.5	4.76 ± 0.45	12.6 ± 3.3	...	11
2.830133	10.2	(8.7)	5.02 ± 0.44	14.3 ± 1.0	6.05 ± 0.37	7.85 ± 2.40	...	12
2.830312	31.3	(30.8)	55.6 ± 1.1	27.6 ± 2.6	4.61 ± 0.98	< 5.32	...	13
2.830398	4.1	(3.3)	21.5 ± 0.8	60.8 ± 1.9	44.8 ± 1.0	74.0 ± 1.9	...	14
2.830560	4.7	(3.5)	19.0 ± 1.7	82.1 ± 6.1	43.4 ± 2.5	280 ± 7	...	15
2.830587	12.6	(11.3)	41.8 ± 2.6	185 ± 7	20.6 ± 6.0	< 7.62	...	16
2.830655	4.5	(3.5)	1.60 ± 0.49	11.1 ± 1.6	26.3 ± 1.1	36.7 ± 3.0	...	17
2.830710	5.9	(5.0)	3.29 ± 0.62	3.95 ± 1.46	1.64 ± 1.12	...	...	18
2.830834	14.9	(13.8)	2.10 ± 0.23	11.0 ± 0.8	4.61 ± 0.30	16.6 ± 2.8	...	19
2.950								
2.947815	11.9	(10.6)	4.35 ± 0.16	< 0.43	< 0.20	...	...	1
2.948133	13.6	(12.4)	4.56 ± 0.17	0.78 ± 0.46	< 0.21	...	...	2
2.949936	10.8	(9.3)	2.18 ± 0.12	< 0.58	< 0.23	...	...	3
2.950319	14.5	(13.4)	7.64 ± 0.21	1.92 ± 0.70	< 0.48	...	...	4
2.950432	6.8	5.0	4.94 ± 0.17	5.36 ± 0.61	< 0.27	...	...	5
2.950655	11.1	(9.6)	16.2 ± 0.2	5.53 ± 0.42	< 0.24	...	...	6
2.951177	19.1	(18.3)	0.74 ± 0.14	< 0.59	< 0.28	...	...	7
2.964^h								
2.963274	14.4	(13.3)	2.66 ± 0.15	< 0.75	< 0.25	...	...	1
2.963415	8.9	(7.1)	1.98 ± 0.12	0.88 ± 0.53	< 0.21	...	...	2
2.963608	7.6	(6.1)	1.14 ± 0.09	< 0.39	< 0.15	...	...	3

TABLE 6—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.963946	13.0	(11.8)	3.89 ± 0.15	1.68 ± 0.65	< 0.27	...	...	4
2.964076	8.8	(7.0)	7.26 ± 0.14	7.89 ± 0.54	0.36 ± 0.21	...	...	5
3.025 ⁱ								
3.024600	7.2	(6.0)	0.66 ± 0.13	< 0.54	< 0.36	...	...	1
3.024766	4.1	(2.7)	0.62 ± 0.11	< 0.35	< 0.36	...	...	2
3.056 ^j								
3.055455	23.9	(23.2)	1.87 ± 0.23	< 0.56	< 0.31	...	...	1
3.055859	16.4	(15.4)	1.79 ± 0.20	< 0.51	...	...	...	2
3.056111	6.0	(4.9)	0.74 ± 0.12	< 0.56	< 0.20	...	...	3
3.067 ^k								
3.066603	10.5	(8.9)	0.97 ± 0.20	< 0.34	< 0.19	< 0.15	...	1
3.066946	10.4	(8.9)	6.69 ± 0.26	8.61 ± 0.39	< 0.23	< 0.21	< 0.43	2
3.067098	6.0	4.9	3.33 ± 0.22	15.1 ± 0.4	< 0.31	< 0.20	< 0.22	3
3.074 ^l								
3.073964	7.1	(5.8)	2.60 ± 0.17	< 0.55	< 0.24	< 0.23	...	1
3.096 ^m								
3.095166	10.9	(9.5)	2.33 ± 0.14	< 0.39	< 0.17	< 0.11	0.57 ± 0.17	1
3.095394	6.3	(3.7)	7.53 ± 0.13	10.3 ± 0.4	< 0.15	< 0.09	0.43 ± 0.14	2
3.095729	10.6	(9.1)	1.31 ± 0.13	0.60 ± 0.42	< 0.35	< 0.12	< 0.32	3
3.095914	5.3	(4.4)	1.46 ± 0.11	0.87 ± 0.32	< 0.14	< 0.09	< 0.22	4
3.135 ⁿ								
3.133446	4.8	(3.8)	3.18 ± 0.34	4.58 ± 0.26	< 0.23	< 0.23	0.26 ± 0.09	1
3.133621	9.9	(8.2)	9.22 ± 0.49	11.7 ± 0.4	< 0.48	0.47 ± 0.18	< 0.13	2
3.133905	19.4	(18.6)	6.50 ± 0.62	4.93 ± 0.50	< 0.42	< 0.26	< 0.36	3
3.134173	4.1	(3.0)	1.08 ± 0.31	< 0.25	< 0.27	< 0.12	< 0.09	4
3.134434	20.1	(19.4)	3.35 ± 0.29	< 0.48	< 0.38	< 0.24	< 0.18	5
3.135223	8.2	(6.7)	0.89 ± 0.16	0.75 ± 0.29	< 0.25	< 0.26	< 0.09	6
3.135488	7.8	(7.1)	2.06 ± 0.18	7.12 ± 0.33	< 0.37	< 0.18	< 0.10	7
3.135658	8.4	(6.9)	3.96 ± 0.22	3.26 ± 0.36	< 0.29	< 0.22	< 0.22	8
3.135817	5.7	(4.5)	0.85 ± 0.26	5.88 ± 0.44	< 0.35	< 0.26	< 0.15	9
3.135860	16.2	(15.3)	7.18 ± 0.41	< 0.74	< 0.57	< 0.46	< 0.23	10
3.155 ^o								
3.152956	14.6	(13.5)	3.37 ± 0.22	< 0.86	< 0.29	< 0.19	< 0.15	1
3.153323	11.7	(10.3)	2.45 ± 0.19	< 0.47	< 0.25	< 0.17	0.25 ± 0.09	2
3.153658	4.1	(3.1)	0.58 ± 0.13	< 0.29	< 0.15	< 0.12	< 0.06	3
3.154100	14.9	(13.8)	4.14 ± 0.21	0.85 ± 0.49	< 0.27	< 0.19	< 0.10	4
3.154541	12.2	(10.9)	1.11 ± 0.19	0.74 ± 0.44	< 0.23	< 0.18	< 0.09	5
3.154991	13.6	(12.4)	0.63 ± 0.19	< 0.46	< 0.25	< 0.42	< 0.09	6
3.156022	27.4	(26.8)	2.63 ± 0.31	< 0.97	< 0.32	< 0.27	0.39 ± 0.15	7
3.174 ^p								
3.172765	7.0	(5.6)	0.34 ± 0.09	< 0.40	< 0.13	< 0.12	< 0.07	1
3.173304	7.0	(5.7)	0.59 ± 0.09	< 0.43	< 0.18	< 0.12	< 0.07	2
3.174358	7.5	(6.1)	0.40 ± 0.10	< 0.28	< 0.13	< 0.13	< 0.07	3
3.174725	7.9	(6.3)	1.18 ± 0.10	0.78 ± 0.28	< 0.14	< 0.13	< 0.12	4
3.175005	8.8	6.1	3.17 ± 0.11	3.05 ± 0.49	0.49 ± 0.15	< 0.13	< 0.09	5
3.175337	14.1	(13.0)	14.3 ± 0.3	10.7 ± 0.7	< 0.33	< 0.29	0.57 ± 0.17	6
3.175407	6.5	5.3	11.9 ± 0.2	29.1 ± 0.5	1.08 ± 0.23	0.77 ± 0.21	< 0.12	7
3.175578	7.6	6.6	6.02 ± 0.13	14.9 ± 0.3	0.62 ± 0.15	0.42 ± 0.14	< 0.08	8
3.175781	3.7	(2.4)	0.49 ± 0.08	0.68 ± 0.23	< 0.12	< 0.10	< 0.06	9

*See Figure 1.

^aC IV $\lambda 1548$ is blended with very weak Si IV $\lambda 1403$ at $z = 3.025$ and $\lambda 1551$ with very weak Si IV $\lambda 1394$ at $z = 3.056$, and are not significantly affected. Si IV $\lambda 1394$ is in the forest and the values are from $\lambda 1403$ alone.

^bSi IV $\lambda 1403$ is blended with Si IV $\lambda 1394$ at $z = 2.726$ but $\lambda 1394$ is clear.

^cSi IV $\lambda 1394$ is blended with Si IV $\lambda 1403$ at $z = 2.702$ but $\lambda 1403$ is clear.

^dSpanning components 5–9 there is very strong Si II and weak related C IV: for these collectively a good fit to the H I Lyman α damping wings is given by $\log N(\text{H I}) \sim 19.4$. C IV $\lambda 1551$ is blended with strong Si II $\lambda 1527$ at $z = 2.830$ and is not used but $\lambda 1548$ is clear. Si II $\lambda 1260$ is in the forest and the values are from $\lambda 1527$.

^eThis system contains a region of unusually high ionization. C IV $\lambda 1548$ is blended with strong Si II $\lambda 1527$ at $z = 2.827$ but $\lambda 1551$ is clear; in component 2 both members of the doublet are saturated and the value (in square brackets) is highly approximate. C II is in the forest: the values for components 2 and 3 are extracted from a complex blend with Si III $\lambda 1207$ at $z = 3.174$ and H I Lyman α but are useful. N V is in the forest but gives good values for the two strong components; these appear slightly broader than is consistent with C IV.

^fThis is a highly complex system with very strong C II and Si II and relatively weak related C IV centred on components 13–19, as well as having several other distributed low ionization components: for these collectively a reasonable fit to the H I Lyman α damping wings is given by $\log N(\text{H I}) \sim 20.3$, reaching the “damped Lyman α ” classification. C II is outside the forest. Si II is obtained from appropriate sections of $\lambda 1527$, which is partially blended with strong C IV $\lambda 1548$ at $z = 2.773$, and of $\lambda 1260$ and $\lambda 1190$, which are in the forest but useful in significant parts. C II is heavily saturated in components 13–18, and Si II $\lambda 1527$ in 14–18, and values for these are not included.

^gThis is a complex system. C II apparently requires an additional strong and narrow component ($\log N(\text{C II}) = 13.9 \pm 0.9$ and $b(\text{C}) = 3.3 \text{ km s}^{-1}$) at $z = 2.830490$, not detected in the other available species and not listed, which probably is an interloper. Si II is from $\lambda 1527$, blended with C IV $\lambda 1551$ at $z = 2.770$ which masks the first few components.

^hC II in component 4 is blended with the outlying narrow component 11 of Si IV $\lambda 1403$ in the $z = 2.770$ system.

ⁱSi IV $\lambda 1403$ is masked by C IV $\lambda 1548$ at $z = 2.646$ but $\lambda 1394$ is clear.

^jIn component 3 C IV $\lambda 1551$ at $z = 2.646$ encroaches on Si IV $\lambda 1394$ and the value is from $\lambda 1403$ alone. C II in component 2 seems contaminated and a value is not included.

^kC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 3.074$ but $\lambda 1548$ is clear. Si II $\lambda 1260$ is outside the forest. The N V values are from $\lambda 1243$ which is in a clear region of the forest.

^lC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 3.067$ but $\lambda 1551$ is clear.

^mN V values are from $\lambda 1243$ which is outside the forest.

ⁿC IV $\lambda 1548$ in components 1–5 is blended with strong Al II $\lambda 1671$ at $z = 2.830$ but $\lambda 1548$ is clear. N V is outside the forest.

^oC IV $\lambda 1551$ in component 7 is blended with Ni II $\lambda 1710$ at $z = 2.770$ but $\lambda 1548$ is clear. N V $\lambda 1243$ is blended with Ni II $\lambda 1370$ at $z = 2.770$ but $\lambda 1239$ is clear.

^pThis is close to z_{em} . Si IV $\lambda 1394$ in component 5 contains an unknown interloper and is not used but $\lambda 1403$ is clear.

TABLE 7
HEAVY ELEMENT ABSORPTION LINES: Q1422+2309C $z_{em} = 3.63^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.666								
2.664759	12.2	...	0.51 ± 0.08	...	...	...	...	1
2.665200	11.0	...	2.32 ± 0.08	...	...	...	...	2
2.665450	11.0	...	1.95 ± 0.10	...	...	...	...	3
2.665655	19.0	...	0.99 ± 0.12	...	...	...	...	4
2.666912	23.8	...	1.75 ± 0.11	...	...	...	...	5
2.683 ^a								
2.682752	12.3	...	5.55 ± 0.45	...	...	...	...	1
2.682904	5.9	...	0.98 ± 0.20	...	...	...	...	2
2.683031	5.5	...	1.18 ± 0.17	...	...	...	...	3
2.698								
2.696855	4.4	...	0.39 ± 0.09	...	...	...	...	1
2.697200	16.3	...	3.73 ± 0.17	...	...	...	...	2
2.697636	11.6	...	9.58 ± 0.16	...	...	...	...	3
2.698077	9.1	...	1.11 ± 0.12	...	...	...	...	4
2.698378	9.6	...	9.62 ± 0.17	...	...	...	...	5
2.698564	15.3	...	7.62 ± 0.19	...	...	...	...	6
2.698860	13.9	...	5.46 ± 0.15	...	...	...	...	7
2.720								
2.719798	12.1	...	1.26 ± 0.13	...	...	...	...	1
2.720051	7.9	...	1.74 ± 0.12	...	...	...	...	2
2.720205	6.9	...	4.84 ± 0.14	...	...	...	...	3
2.720681	27.5	...	0.98 ± 0.16	...	...	...	...	4
2.749 ^b								
2.748373	7.4	...	0.78 ± 0.20	...	...	...	...	1
2.748587	6.0	...	0.92 ± 0.18	...	...	...	...	2
2.748750	6.6	...	1.64 ± 0.20	...	...	...	...	3
2.748876	5.1	(3.6)	11.8 ± 0.3	76.8 ± 3.3	...	...	...	4
2.748966	7.9	(6.5)	9.43 ± 0.32	27.5 ± 1.7	...	...	...	5
2.749170	6.5	(5.3)	8.29 ± 0.22	3.30 ± 0.68	...	...	...	6
2.749402	8.4	...	1.65 ± 0.26	...	...	...	...	7
2.749660	29.1	...	5.23 ± 0.89	...	...	...	...	8
2.749847	6.6	...	3.36 ± 0.27	...	...	...	...	9
2.772								
2.771655	8.2	...	1.36 ± 0.10	...	...	...	...	1
2.797								
2.796525	3.9	...	0.61 ± 0.16	...	...	...	...	1
2.796748	15.6	...	2.29 ± 0.33	...	...	...	...	2
2.810								
2.809759	8.4	...	1.82 ± 0.19	...	...	...	...	1
2.895								
2.895077	16.6	...	2.04 ± 0.19	...	...	...	...	1
2.895430	13.4	...	7.51 ± 0.27	...	...	...	...	2
2.895596	24.7	...	5.03 ± 0.34	...	...	...	...	3
2.908								
2.907666	7.1	...	0.35 ± 0.10	...	...	...	...	1
2.908035	15.6	...	0.62 ± 0.15	...	...	...	...	2
2.910								
2.909673	11.1	...	2.54 ± 0.23	...	...	...	...	1
2.946 ^c								
2.945131	4.1	...	0.67 ± 0.21	...	...	...	...	1
2.945459	11.7	...	1.41 ± 0.37	...	...	...	...	2
2.947497	8.3	...	3.11 ± 0.26	...	...	...	...	3
2.962 ^d								
2.960717	21.5	...	2.15 ± 0.26	...	...	...	...	1
2.961013	11.0	...	2.22 ± 0.19	...	...	...	...	2
2.961504	8.3	...	3.03 ± 0.16	...	...	...	...	3

TABLE 7—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
2.961843	10.2	...	14.7 ± 0.2	...	...	...	< 0.99	4
2.962061	7.4	...	6.12 ± 0.18	...	...	...	...	5
2.962344	10.1	...	6.82 ± 0.19	...	...	...	...	6
2.971 ^e								
2.970982	17.0	...	0.58 ± 0.50	...	...	...	...	1
2.971423	14.3	...	2.05 ± 0.46	...	...	...	...	2
2.971613	3.5	...	0.43 ± 0.12	...	...	...	...	3
2.976								
2.975799	23.4	...	2.55 ± 0.24	...	...	...	...	1
2.976200	10.6	...	6.54 ± 0.18	...	...	...	...	2
2.999								
2.999190	9.4	...	1.19 ± 0.40	...	...	...	...	1
2.999204	25.1	...	5.03 ± 0.63	...	...	...	...	2
3.036								
3.035037	4.7	...	0.95 ± 0.13	...	...	...	...	1
3.036486	12.7	...	1.40 ± 0.20	...	...	...	...	2
3.064 ^f								
3.063205	6.6	(5.4)	1.52 ± 0.26	< 0.20	...	...	...	1
3.063418	5.8	(4.8)	2.57 ± 0.38	< 0.27	...	...	...	2
3.063467	17.5	(16.6)	3.98 ± 0.63	< 0.48	...	...	...	3
3.063973	18.8	(18.0)	2.49 ± 0.43	< 0.32	...	...	...	4
3.064434	9.2	(7.4)	1.71 ± 0.49	< 0.22	...	...	...	5
3.071								
3.071076	7.2	(5.7)	4.40 ± 0.25	< 0.36	...	...	...	1
3.086 ^g								
3.086040	5.6	(4.4)	1.06 ± 0.28	< 0.39	...	...	...	1
3.086314	2.7	(2.2)	0.52 ± 0.15	< 0.28	...	...	...	2
3.086651	7.1	(5.9)	5.97 ± 0.31	< 0.39	...	...	...	3
3.086815	8.6	(6.8)	2.10 ± 0.31	< 0.45	...	...	...	4
3.090 ^h								
3.089876	13.0	(11.8)	10.0 ± 0.4	2.27 ± 0.99	...	...	...	1
3.090256	14.1	(13.0)	14.1 ± 0.3	12.3 ± 0.7	...	...	...	2
3.090509	6.9	(5.5)	4.22 ± 0.23	4.00 ± 0.45	...	...	...	3
3.090769	7.0	(5.6)	2.94 ± 0.23	3.12 ± 0.80	...	...	...	4
3.091044	8.7	(6.9)	10.6 ± 0.2	9.16 ± 0.84	...	...	...	5
3.095								
3.094865	34.0	(33.6)	2.07 ± 0.79	< 4.90	...	...	...	1
3.135 ⁱ								
3.132487	25.2	(24.6)	2.76 ± 0.46	< 2.92	...	...	...	1
3.133928	29.1	(28.6)	10.4 ± 0.8	10.3 ± 1.1	...	...	...	2
3.134476	12.3	(11.0)	7.34 ± 0.66	5.86 ± 0.78	...	...	...	3
3.136880	11.0	(9.6)	1.47 ± 0.98	5.73 ± 2.40	...	...	...	4
3.137120	13.5	(12.3)	5.37 ± 0.97	10.8 ± 2.5	...	...	...	5
3.191								
3.191350	3.2	(2.2)	0.44 ± 0.12	0.91 ± 0.47	...	...	...	1
3.191440	8.9	(7.1)	1.09 ± 0.20	< 0.74	...	...	...	2
3.240 ^j								
3.240169	19.6	(18.9)	2.02 ± 0.31	< 1.12	< 0.17	...	...	1
3.240658	6.0	(3.9)	0.80 ± 0.17	< 0.57	< 0.21	...	...	2
3.257								
3.256875	3.7	(2.4)	0.33 ± 0.13	< 0.41	< 0.15	...	...	1
3.257276	11.1	(9.6)	0.64 ± 0.21	< 1.79	< 1.06	...	...	2
3.265 ^k								
3.264775	24.1	(23.5)	0.74 ± 0.34	...	< 0.70	...	...	1
3.265398	3.7	(2.4)	0.69 ± 0.14	...	< 0.18	...	...	2
3.265741	14.8	(13.7)	3.75 ± 0.26	< 0.91	< 0.30	...	...	3

TABLE 7—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.381 ^l								
3.380044	22.5	(21.9)	6.52 ± 0.61	< 1.64	< 0.54	...	...	1
3.380465	7.0	(5.7)	0.30 ± 0.28	...	< 0.30	...	...	2
3.380676	13.1	(11.9)	2.53 ± 0.42	< 1.01	< 0.31	...	...	3
3.381392	10.9	(9.4)	4.10 ± 0.38	< 0.87	< 0.28	...	...	4
3.381652	9.4	(7.6)	14.0 ± 0.4	< 0.76	< 0.27	...	...	5
3.382017	11.5	(10.1)	6.79 ± 0.40	< 0.89	< 0.29	...	...	6
3.382285	10.0	(8.4)	8.68 ± 0.37	2.81 ± 1.06	< 0.28	...	...	7
3.382676	8.2	(6.3)	3.27 ± 0.38	< 1.19	< 0.31	...	...	8
3.382871	34.1	(33.7)	4.73 ± 0.91	< 2.29	< 0.65	...	...	9
3.411 ^m								
3.410989	23.7	(23.0)	1.85 ± 0.35	< 2.55	< 0.52	...	...	1
3.411523	18.1	(17.2)	7.21 ± 0.33	5.11 ± 2.17	...	...	...	2
3.449 ⁿ								
3.446200	14.8	(13.7)	2.95 ± 0.43	< 1.13	< 0.48	...	...	1
3.446574	12.6	(11.4)	1.51 ± 0.39	4.72 ± 0.89	< 0.35	...	...	2
3.446894	6.4	5.6	8.18 ± 0.34	28.2 ± 0.8	< 0.32	...	...	3
3.447156	9.4	(7.8)	7.56 ± 0.41	16.8 ± 0.8	< 0.32	...	...	4
3.447410	10.9	(9.5)	19.1 ± 0.6	36.9 ± 1.0	< 0.44	...	...	5
3.448211	12.4	(11.1)	1.15 ± 0.36	1.94 ± 0.85	< 0.84	...	...	6
3.448625	13.9	(12.7)	3.44 ± 0.46	17.7 ± 1.0	2.38 ± 0.36	...	...	7
3.449267	15.6	(14.6)	2.48 ± 0.59	6.39 ± 1.00	< 0.37	...	...	8
3.450546	7.4	(6.0)	0.89 ± 0.31	< 0.96	< 0.59	...	...	9
3.451340	16.0	(15.0)	10.5 ± 0.7	5.83 ± 1.02	< 0.36	...	...	10
3.452078	7.9	(6.3)	0.82 ± 0.29	3.51 ± 0.70	< 0.33	...	...	11
3.480 ^o								
3.479479	15.3	(14.2)	1.75 ± 0.45	< 1.10	< 0.70	< 0.46	...	1
3.479781	3.7	(2.4)	0.95 ± 0.25	< 0.48	< 0.32	< 0.09	...	2
3.480366	8.4	(6.5)	0.88 ± 0.33	< 0.68	< 0.44	< 0.22	...	3
3.494 ^p								
3.493290	14.6	(13.5)	2.02 ± 0.37	< 1.00	< 0.78	< 0.23	...	1
3.494847	6.6	(5.8)	2.08 ± 0.25	< 0.90	< 0.38	< 0.14	...	2
3.515 ^q								
3.514508	11.3	(9.9)	0.71 ± 0.27	2.73 ± 1.60	< 0.30	< 0.38	< 0.65	1
3.514639	6.2	(5.0)	5.79 ± 0.28	5.69 ± 1.28	< 0.52	< 0.33	< 0.52	2
3.514781	11.8	(10.5)	0.85 ± 0.33	< 3.74	< 0.52	< 0.42	< 0.67	3
3.514988	10.4	(8.9)	1.65 ± 0.25	< 1.21	< 0.31	< 0.33	< 0.56	4
3.538 ^r								
3.534573	22.7	(22.0)	5.12 ± 0.41	< 1.26	< 0.30	< 0.60	< 0.39	1
3.534873	3.3	(2.2)	1.55 ± 0.20	< 0.51	< 0.21	< 0.25	< 0.28	2
3.535056	7.4	(5.1)	4.60 ± 0.26	< 0.63	...	< 0.30	< 0.19	3
3.535562	19.5	(18.7)	9.82 ± 0.44	< 1.82	...	< 0.57	< 0.31	4
3.535939	12.8	(11.6)	27.2 ± 0.6	38.2 ± 1.3	< 0.41	< 0.52	< 0.33	5
3.536132	5.5	(3.7)	4.67 ± 0.42	21.7 ± 0.9	1.27 ± 0.20	< 0.31	< 0.28	6
3.536367	35.7	(35.3)	32.1 ± 1.0	37.0 ± 2.7	1.27 ± 0.63	...	...	7
3.536634	9.5	(8.9)	< 0.45	6.48 ± 1.18	2.75 ± 0.27	2.12 ± 0.51	< 0.40	8
3.537240	6.6	(5.5)	5.93 ± 0.61	56.4 ± 1.9	2.60 ± 0.41	3.03 ± 0.64	< 0.30	9
3.537303	19.1	(18.3)	7.76 ± 1.21	32.5 ± 3.0	5.87 ± 0.82	2.26 ± 1.25	< 0.72	10
3.537475	7.1	4.8	4.70 ± 0.49	12.0 ± 1.1	< 0.37	0.73 ± 0.46	< 0.29	11
3.538010	20.6	(19.8)	4.50 ± 0.41	7.58 ± 1.23	< 0.28	< 0.56	< 0.34	12
3.538598	22.2	(21.5)	38.6 ± 0.8	69.3 ± 2.0	1.16 ± 0.42	...	< 0.46	13
3.538702	6.1	4.5	24.8 ± 1.0	74.3 ± 2.0	1.20 ± 0.26	0.65 ± 0.40	< 0.28	14
3.538794	5.2	(3.8)	2.64 ± 0.53	13.4 ± 1.5	0.98 ± 0.21	1.16 ± 0.33	< 0.31	15
3.539293	9.1	(7.5)	22.2 ± 0.6	21.6 ± 1.3	< 0.32	< 0.53	< 0.43	16
3.539503	6.8	(5.2)	8.83 ± 0.50	8.23 ± 1.31	< 0.32	< 0.43	< 0.32	17
3.539512	29.2	(28.7)	7.72 ± 1.19	< 3.71	< 0.84	< 1.28	< 0.66	18
3.539894	8.7	(6.8)	< 0.52	< 1.14	1.21 ± 0.32	1.18 ± 0.42	< 0.39	19

TABLE 7—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.540026	5.7	(4.6)	0.54 ± 0.27	5.44 ± 0.73	1.08 ± 0.22	0.96 ± 0.29	...	20
3.540205	6.8	(5.9)	0.97 ± 0.32	2.27 ± 0.88	2.55 ± 0.27	3.11 ± 0.38	< 0.27	21
3.540280	32.9	(32.4)	5.22 ± 0.74	< 7.86	< 1.67	...	...	22
3.541446	8.5	(6.9)	2.60 ± 0.26	< 0.84	< 0.22	< 4.15	< 0.51	23
3.588 ^a								
3.586827	15.6	(14.6)	9.40 ± 0.23	16.1 ± 1.1	< 0.48	...	< 0.41	1
3.587146	16.0	(15.0)	7.07 ± 0.21	4.72 ± 1.09	< 0.58	...	< 0.48	2
3.588866	18.7	(17.9)	2.53 ± 0.19	< 1.09	< 0.49	< 0.55	< 0.86	3
3.589211	9.8	(8.1)	2.97 ± 0.15	< 1.19	< 0.36	< 0.40	< 0.48	4
3.589570	15.0	(14.0)	0.48 ± 0.17	< 2.13	< 0.49	< 0.80	< 0.44	5
3.624 ^b								
3.623361	7.2	(4.7)	3.02 ± 0.18	< 0.95	< 0.32	< 0.23	0.85 ± 0.20	1
3.623519	5.7	(4.5)	12.9 ± 0.3	< 0.58	< 0.36	< 0.24	4.84 ± 0.35	2
3.623641	5.9	(4.7)	9.83 ± 0.24	< 0.57	< 0.34	< 0.25	8.21 ± 0.28	3
3.623830	7.8	(6.6)	7.45 ± 0.19	< 0.62	< 0.48	< 0.26	2.11 ± 0.23	4
3.624179	10.6	(9.1)	13.1 ± 0.3	< 0.76	< 0.58	< 0.31	5.41 ± 0.27	5
3.624333	4.4	(3.0)	5.21 ± 0.33	2.45 ± 0.62	< 0.49	< 0.43	2.09 ± 0.23	6
3.624406	5.7	(4.7)	18.3 ± 0.4	2.72 ± 0.69	< 0.42	< 0.29	1.76 ± 0.30	7
3.624632	9.8	(8.1)	3.99 ± 0.20	< 0.67	< 0.65	< 0.29	0.71 ± 0.22	8
3.624886	8.6	(6.7)	1.95 ± 0.17	< 0.61	< 0.40	< 0.26	0.52 ± 0.19	9
3.625242	12.9	(11.6)	3.48 ± 0.21	< 0.84	< 0.41	< 0.33	0.67 ± 0.27	10

*See Figure 1. For this object, in addition to the sky background including atmospheric line emission whose mean level is removed by the normal sky subtraction procedure (with related residual noise enhancement), both weak and strong atmospheric H₂O and O₂ absorption bands here are significantly present in the observed wavelength range and have to be taken intricately into account while assessing the structures of the QSO absorber systems within the fitting process (see text). The lines in these bands are intrinsically very narrow compared with the QSO absorber components except in the most heavily absorbed regions where information is unavoidably obscured. However, the QSO data have been reduced to vacuum, heliocentric redshifts so the apparent positions and widths of the atmospheric lines seen in this frame of reference reflect the integrated collective epochs of observation: here for Q1422+2309C the specific lengths and separation of observing runs become manifest as a mild broadening and pronounced spectral doubling (and therefore a related apparent weakening) of the atmospheric lines.

^aC IV $\lambda 1548$ is blended with Si IV $\lambda 1394$ at $z = 3.090$ but $\lambda 1551$ is clear.

^bC IV $\lambda 1548$ in components 1 and 2 is blended with Si IV $\lambda 1403$ at $z = 3.135$ but $\lambda 1551$ is clear. Although Si IV is in the forest, for $\lambda 1394$ components 4–6 are in a relatively clear region.

^cC IV $\lambda 1548$ in components 1 and 2 is blended with Si IV $\lambda 1394$ at $z = 3.381$ but $\lambda 1551$ is clear.

^dThe N V upper limit is from $\lambda 1243$ in a clear region of the forest.

^eC IV $\lambda 1548$ is blended with Si IV $\lambda 1394$ at $z = 3.411$ and Si IV $\lambda 1403$ at $z = 3.381$ but $\lambda 1551$ is clear.

^fC IV $\lambda 1548$ is mildly contaminated by atmospheric line absorption and in component 5 is blended with Si IV $\lambda 1394$ at $z = 3.515$ while $\lambda 1551$ contains both atmospheric line absorption and emission and, also in component 5, is blended with C IV $\lambda 1548$ at $z = 3.071$: acceptable values are obtained largely through $\lambda 1548$. Si IV $\lambda 1403$ is masked by Si IV $\lambda 1394$ at $z = 3.090$ and C IV $\lambda 1548$ at $z = 2.683$ and the upper limits are from $\lambda 1394$.

^gC IV $\lambda 1548$ is blended with Si IV $\lambda 1394$ at $z = 3.538$ but $\lambda 1551$ is clear. Si IV $\lambda 1403$ in component 4 is blended with component 1 of C IV $\lambda 1551$ at $z = 2.698$ and here the upper limit is from $\lambda 1394$.

^hC IV $\lambda 1548$ contains Si IV $\lambda 1403$ at $z = 3.515$ but $\lambda 1551$ is clear. Si IV $\lambda 1394$ is in a blend with C IV $\lambda 1548$ at $z = 2.683$, very weak Si IV $\lambda 1403$ at $z = 3.064$ and an unidentified interloper at observed wavelength $\lambda 5700.35$ near component 1, while $\lambda 1403$ also has some unknown contamination covering component 1, but from the available complementary regions acceptable values are obtained for all the other components.

ⁱSi IV $\lambda 1394$ in component 1 is masked by C IV $\lambda 1548$ at $z = 2.720$ while components 4 and 5 of $\lambda 1403$ are blended with C IV $\lambda 1548$ at $z = 2.749$, but together acceptable values are obtained.

^jC II is outside the forest.

^kSi IV $\lambda 1394$ in the weak components 1 and 2 is contaminated by atmospheric line absorption and $\lambda 1403$ is in a noisy region, making values here too uncertain to include.

¹This is nominally a partial Lyman limit system with total $\log N(\text{H I}) \sim 17.2$ but C II is very weak. Si IV $\lambda 1394$ in component 2 is masked by an unidentified feature and in components 7 and 8 is blended with C IV $\lambda 1548$ at $z = 2.946$ while $\lambda 1403$ in components 1 and 2 is blended with C IV $\lambda 1551$ at $z = 2.962$, in components 8 and 9 with C IV $\lambda 1548$ at $z = 2.971$ and in component 8 also with very weak Si IV $\lambda 1394$ at $z = 3.411$: nevertheless, acceptable values are obtained for all but component 2. C II in components 8 and 9 is blended with weak C IV $\lambda 1551$ at $z = 2.772$ but together with $\lambda 1548$ of the latter the upper limits obtained are reliable.

^mSi IV $\lambda 1394$ is blended with C IV $\lambda 1548$ at $z = 2.971$ and borders on Si IV $\lambda 1403$ at $z = 3.381$ but $\lambda 1403$ is clear. C II in component 2 is masked by C IV $\lambda 1551$ at $z = 2.797$.

ⁿC IV is partially contaminated by strong atmospheric line absorption features but by including these in the fitting process for both lines of the doublet acceptable values are obtained in all components.

^oSi IV $\lambda 1403$ is contaminated by atmospheric line absorption and the upper limits are from $\lambda 1394$. Si II $\lambda 1260$ is outside the forest.

^pSi IV $\lambda 1403$ is blended with C IV $\lambda 1548$ at $z = 3.071$ and C IV $\lambda 1551$ at $z = 3.064$ and there is also contamination by atmospheric line absorption: the upper limits are from $\lambda 1394$.

^qC IV is contaminated by atmospheric line absorption but good values are obtained in all components from complementary regions of the doublet. Si IV $\lambda 1394$ is mildly affected by atmospheric line absorption and is blended with C IV $\lambda 1548$ at $z = 3.064$ while $\lambda 1403$ is blended with strong C IV $\lambda 1548$ at $z = 3.090$ but taken together useful values are obtained. N V upper limits are from $\lambda 1243$ in a clear region of the forest.

^rThis is a highly complex system. C IV is mildly contaminated by atmospheric line absorption but good values are obtained overall. Si IV $\lambda 1394$ in components 14–17 is blended with C IV $\lambda 1548$ at $z = 3.086$ and $\lambda 1403$ in component 12 has some interference from atmospheric line emission, but together good values are obtained. C II values in components 3 and 4 are too uncertain to use, due to blending with C IV $\lambda 1548$ at $z = 2.910$. N V $\lambda 1243$ is outside the forest and yields good upper limits.

^sC II in component 2 is blended with C IV $\lambda 1551$ at $z = 2.946$ but a useful upper limit is obtained from close analysis of the C IV doublet. Si II in components 1 and 2 seems too strong relative to C II and probably contains an unidentified interloper, and is not used. N V is outside the forest; $\lambda 1239$ in components 3–5 is blended with C IV $\lambda 1551$ at $z = 2.666$ and $\lambda 1243$ in components 1 and 2 is masked by Si IV $\lambda 1394$ at $z = 3.090$ and C IV $\lambda 1548$ at $z = 2.683$ but taken together useful upper limits are obtained.

^tThis is close to z_{em} . C IV $\lambda 1551$ has some contamination by atmospheric line absorption but $\lambda 1548$ is not significantly affected. Si IV $\lambda 1403$ is mildly contaminated by atmospheric line absorption but $\lambda 1394$ is clear.

TABLE 8
HEAVY ELEMENT ABSORPTION LINES: Q1645+5520 $z_{em} = 4.10^*$

z	$b(C)$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.015 ^a								
3.015026	7.6	...	0.33 ± 0.14	...	...	...	...	1
3.077 ^b								
3.076957	9.4	...	1.87 ± 0.17	...	...	...	...	1
3.077197	7.5	...	6.25 ± 0.20	...	...	...	...	2
3.129								
3.128686	9.6	...	5.63 ± 0.18	...	...	...	...	1
3.128941	8.8	...	3.32 ± 0.17	...	...	...	...	2
3.129349	12.3	...	0.58 ± 0.17	...	...	...	...	3
3.129694	3.9	...	0.39 ± 0.12	...	...	...	...	4
3.162								
3.161200	10.7	...	1.53 ± 0.18	...	...	...	...	1
3.161467	11.1	...	2.19 ± 0.19	...	...	...	...	2
3.161877	6.9	...	0.86 ± 0.15	...	...	...	...	3
3.162148	8.2	...	3.78 ± 0.18	...	...	...	...	4
3.162442	17.0	...	4.51 ± 0.23	...	...	...	...	5
3.162982	20.4	...	2.00 ± 0.23	...	...	...	...	6
3.163669	14.8	...	1.42 ± 0.20	...	...	...	...	7
3.193 ^c								
3.191938	12.3	...	1.57 ± 0.16	...	...	...	...	1
3.192421	6.7	...	2.94 ± 0.15	...	...	...	...	2
3.192914	54.9	...	11.8 ± 0.6	...	...	...	...	3
3.193257	15.8	...	22.1 ± 0.6	...	...	...	...	4
3.193301	26.4	...	10.5 ± 0.8	...	...	...	...	5
3.197								
3.197438	21.8	...	2.38 ± 0.17	...	...	...	...	1
3.217								
3.216331	9.5	...	2.34 ± 0.17	...	...	...	...	1
3.216788	24.6	...	3.71 ± 0.26	...	...	...	...	2
3.262								
3.261969	7.3	...	1.58 ± 0.25	...	...	...	...	1
3.262136	12.3	...	0.69 ± 0.19	...	...	...	...	2
3.289								
3.287686	27.0	...	3.72 ± 0.28	...	...	...	...	1
3.287971	4.8	...	0.96 ± 0.15	...	...	...	...	2
3.288192	13.6	...	10.5 ± 0.2	...	...	...	...	3
3.288662	16.6	...	14.1 ± 0.3	...	...	...	...	4
3.288957	6.2	...	3.93 ± 0.29	...	...	...	...	5
3.289017	18.0	...	10.3 ± 0.4	...	...	...	...	6
3.290072	21.9	...	4.97 ± 0.28	...	...	...	...	7
3.322 ^d								
3.321727	21.4	...	1.74 ± 0.22	...	...	...	...	1
3.322327	10.0	...	2.34 ± 0.18	...	...	...	...	2
3.322627	11.5	...	3.72 ± 0.19	...	...	...	...	3
3.323030	19.4	...	2.38 ± 0.25	...	...	...	...	4
3.341 ^e								
3.340588	10.5	...	1.06 ± 0.18	...	...	...	...	1
3.340847	7.7	...	1.08 ± 0.19	...	...	...	...	2
3.341160	9.0	...	1.35 ± 0.23	...	...	...	...	3
3.341462	19.6	...	1.43 ± 0.35	...	...	...	...	4
3.341963	6.0	...	0.60 ± 0.26	...	...	...	...	5
3.348								
3.347684	11.7	...	0.29 ± 0.16	...	...	...	...	1
3.348334	3.0	...	0.20 ± 0.11	...	...	...	...	2
3.348930	4.2	...	0.15 ± 0.10	...	...	...	...	3
3.349228	3.3	...	0.17 ± 0.13	...	...	...	...	4

TABLE 8—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.355								
3.354884	38.2	...	2.04 ± 0.30	...	...	...	...	1
3.355420	4.2	...	0.57 ± 0.13	...	...	...	...	2
3.355849	13.3	...	1.75 ± 0.19	...	...	...	...	3
3.421 ^f								
3.420509	6.9	(5.7)	4.12 ± 0.24	7.72 ± 0.37	...	...	...	1
3.420657	5.5	(4.4)	2.20 ± 0.13	15.8 ± 0.4	...	...	...	2
3.420838	7.8	(6.3)	2.90 ± 0.12	6.15 ± 0.38	...	...	...	3
3.421212	15.4	(14.4)	1.09 ± 0.14	< 3.24	...	...	...	4
3.468 ^g								
3.467141	20.2	(19.5)	7.25 ± 0.44	4.44 ± 0.74	...	...	...	1
3.467446	9.1	(7.3)	0.77 ± 0.26	3.40 ± 0.52	...	...	...	2
3.467751	12.4	(11.1)	7.70 ± 0.32	9.72 ± 0.60	...	...	...	3
3.467968	9.1	(7.3)	4.75 ± 0.27	6.65 ± 0.49	...	...	...	4
3.514 ^h								
3.513426	3.8	...	0.18 ± 0.11	...	...	...	...	1
3.513691	7.9	...	0.57 ± 0.15	...	...	...	...	2
3.514141	12.0	...	2.10 ± 0.21	...	...	...	...	3
3.514405	8.0	...	6.32 ± 0.20	...	...	...	...	4
3.544 ⁱ								
3.541717	23.7	(23.1)	4.70 ± 0.41	7.15 ± 1.42	...	...	...	1
3.542056	10.5	(8.9)	5.18 ± 0.31	12.8 ± 1.1	...	...	...	2
3.542427	13.6	(12.5)	26.7 ± 0.5	79.7 ± 1.6	...	...	...	3
3.542665	11.9	(10.6)	27.2 ± 0.7	43.5 ± 1.8	...	...	...	4
3.542967	17.2	(16.3)	29.7 ± 0.7	27.6 ± 1.9	...	...	...	5
3.543164	5.7	(4.8)	6.26 ± 0.40	< 1.26	...	...	...	6
3.543341	8.5	(7.0)	13.8 ± 0.4	14.4 ± 1.2	...	...	...	7
3.543622	9.6	(7.3)	10.2 ± 0.3	21.1 ± 1.0	...	...	...	8
3.544162	37.0	(36.6)	22.5 ± 0.6	10.7 ± 2.1	...	...	...	9
3.544469	5.9	4.0	13.2 ± 0.4	37.3 ± 0.9	...	...	...	10
3.544663	3.7	(2.4)	2.49 ± 0.22	3.88 ± 0.53	...	...	...	11
3.544837	6.5	4.3	17.1 ± 0.4	18.3 ± 0.7	...	...	...	12
3.545112	12.2	(10.9)	2.20 ± 0.30	3.21 ± 0.85	...	...	...	13
3.545386	13.5	(12.4)	0.98 ± 0.38	6.37 ± 1.06	...	...	...	14
3.545645	20.6	(19.9)	1.22 ± 0.44	6.95 ± 1.34	...	...	...	15
3.546023	9.6	(8.1)	0.84 ± 0.24	2.80 ± 0.71	...	...	...	16
3.567								
3.566854	18.6	(17.8)	4.43 ± 0.30	< 0.76	...	...	...	1
3.690 ^j								
3.689699	3.7	(2.5)	0.71 ± 0.13	< 0.80	< 0.17	...	...	1
3.689963	9.9	(8.2)	1.89 ± 0.19	< 0.98	< 0.23	...	...	2
3.690267	10.2	(8.6)	4.35 ± 0.20	1.41 ± 0.98	< 0.24	...	...	3
3.690600	9.7	(8.0)	1.57 ± 0.18	< 0.97	...	...	...	4
3.752 ^k								
3.751237	4.8	(3.8)	2.13 ± 0.27	< 0.78	...	...	...	1
3.751557	30.1	(29.6)	6.29 ± 0.60	< 1.40	...	...	...	2
3.751980	6.0	4.4	18.1 ± 0.5	4.25 ± 0.61	< 0.32	...	...	3
3.752309	11.2	(9.8)	7.66 ± 0.43	2.12 ± 0.82	< 0.49	...	...	4
3.752474	3.3	(2.2)	3.17 ± 1.04	10.7 ± 1.2	< 0.43	...	...	5
3.752535	6.6	(5.1)	28.2 ± 1.3	23.0 ± 1.3	< 0.53	...	...	6
3.752742	5.4	(4.4)	10.6 ± 0.6	18.5 ± 1.0	< 0.43	...	...	7
3.752798	17.8	(17.0)	7.86 ± 0.76	4.31 ± 1.64	...	...	...	8
3.753312	5.9	(4.9)	2.74 ± 0.34	2.13 ± 0.59	< 0.27	...	...	9
3.753501	4.9	3.6	5.19 ± 0.64	12.3 ± 1.0	< 0.45	...	...	10
3.753573	11.1	(9.6)	13.6 ± 0.7	2.35 ± 1.21	< 0.86	...	...	11
3.759 ^l								
3.758220	13.2	(12.0)	10.2 ± 0.5	14.5 ± 0.9	...	...	...	1
3.758825	6.9	(5.8)	1.07 ± 0.28	< 0.67	< 0.35	...	...	2

TABLE 8—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.779 ^m								
3.779232	9.3	(7.5)	2.45 ± 0.27	< 0.99	< 0.29	...	...	1
3.811								
3.810675	15.3	(14.3)	1.34 ± 0.28	< 1.40	< 0.76	...	...	1
3.811041	7.2	(6.2)	3.78 ± 0.22	< 1.39	< 0.43	...	...	2
3.863 ⁿ								
3.863018	8.6	(6.8)	0.80 ± 0.25	< 1.52	...	...	...	1
3.863389	12.8	(11.6)	2.35 ± 0.31	2.21 ± 0.84	...	...	...	2
3.881 ^o								
3.880046	49.7	(49.4)	12.1 ± 0.6	9.92 ± 1.49	< 0.72	...	...	1
3.880840	5.3	(4.3)	1.24 ± 0.22	< 0.50	...	...	...	2
3.921 ^p								
3.920918	10.5	(9.7)	2.93 ± 0.40	19.0 ± 0.60	0.59 ± 0.34	< 0.27	...	1
3.921157	16.2	(15.7)	14.9 ± 0.69	3.92 ± 0.92	< 0.51	< 0.41	...	2
3.921199	7.9	(6.8)	5.66 ± 0.42	21.3 ± 0.54	0.91 ± 0.30	< 0.23	...	3
3.921509	7.7	(6.6)	3.70 ± 0.35	14.3 ± 0.54	< 0.32	< 0.24	...	4
3.921682	6.4	(5.1)	3.47 ± 0.32	2.77 ± 0.45	< 0.29	< 0.22	...	5
3.976 ^q								
3.974237	34.1	(33.6)	2.60 ± 0.53	< 2.37	...	...	...	1
3.975244	12.9	(11.6)	1.49 ± 0.30	< 1.24	...	...	...	2
3.976158	32.9	...	4.62 ± 0.51	...	...	...	...	3
3.994								
3.993795	11.6	(10.3)	3.40 ± 0.25	< 0.91	< 0.44	...	...	1
3.994076	8.8	(7.1)	2.00 ± 0.22	< 0.74	< 0.43	...	...	2
4.024 ^r								
4.022713	18.2	...	1.78 ± 0.41	...	< 0.41	...	< 0.28	1
4.023240	9.4	(7.7)	3.28 ± 0.36	5.39 ± 0.80	< 0.33	...	< 0.23	2
4.023394	4.1	(2.9)	1.57 ± 0.32	6.25 ± 0.69	< 0.25	...	< 0.19	3
4.023609	11.7	(10.4)	8.46 ± 0.42	25.7 ± 0.9	0.96 ± 0.34	...	< 0.28	4
4.023930	7.5	(6.3)	3.70 ± 0.31	1.74 ± 0.66	< 0.53	...	< 0.20	5
4.024154	4.3	(3.2)	1.20 ± 0.23	< 0.76	< 0.50	...	< 0.16	6
4.024557	10.4	(8.9)	1.62 ± 0.30	< 0.71	< 0.55	...	< 0.21	7
4.031 ^s								
4.029082	6.1	(5.1)	1.29 ± 0.35	< 0.85	< 0.30	< 0.40	< 0.19	1
4.029235	8.3	(7.1)	1.78 ± 0.42	2.29 ± 0.99	< 0.38	< 0.48	< 0.27	2
4.029449	8.2	(6.8)	7.84 ± 0.48	2.31 ± 0.95	< 0.36	...	< 0.26	3
4.029637	6.7	(5.5)	17.3 ± 0.8	10.2 ± 1.5	< 0.66	...	< 0.24	4
4.029792	7.2	(6.0)	9.66 ± 1.85	84.4 ± 4.9	< 2.77	< 12.30	< 0.60	5
4.029875	8.0	(6.6)	2.66 ± 2.52	5.68 ± 5.29	67.3 ± 4.1	102 ± 13	< 0.80	6
4.029986	8.4	(6.7)	19.4 ± 1.5	17.9 ± 2.1	8.40 ± 1.98	< 15.2	< 0.43	7
4.030165	5.1	(4.1)	2.74 ± 0.49	4.03 ± 0.96	38.8 ± 1.1	119 ± 7	< 0.24	8
4.030371	9.3	(7.6)	13.3 ± 0.6	62.1 ± 1.8	33.3 ± 0.8	72.5 ± 4.7	< 0.25	9
4.030507	4.3	(3.5)	0.19 ± 0.53	2.64 ± 1.54	42.8 ± 1.6	68.4 ± 3.7	< 0.23	10
4.030608	7.4	(6.1)	5.24 ± 0.64	47.4 ± 2.0	4.28 ± 0.82	7.58 ± 1.49	< 0.29	11
4.030774	11.7	(10.3)	7.53 ± 0.53	25.0 ± 1.8	0.80 ± 0.44	< 0.96	< 0.33	12
4.031528	26.0	(25.4)	5.34 ± 1.05	6.69 ± 2.96	< 0.89	...	< 0.67	13
4.031661	15.1	(14.1)	3.60 ± 0.85	< 2.90	< 0.69	< 1.00	< 0.43	14
4.031999	16.2	(15.3)	1.05 ± 0.47	< 1.08	< 0.76	...	< 0.26	15
4.032692	6.4	(5.5)	0.46 ± 0.26	< 0.78	< 0.22	< 0.35	< 0.16	16
4.033157	18.1	(17.3)	3.04 ± 0.42	< 2.47	< 0.38	...	< 0.36	17
4.037 ^t								
4.035726	11.3	(9.9)	4.98 ± 0.48	3.77 ± 1.14	< 0.50	< 0.34	< 0.20	1
4.036301	11.8	(10.5)	14.1 ± 0.4	28.6 ± 1.6	1.30 ± 0.56	< 0.46	< 0.20	2
4.036650	6.2	(5.0)	6.61 ± 0.34	6.57 ± 1.23	< 0.46	< 0.27	< 0.25	3
4.037141	13.9	(12.8)	6.62 ± 0.41	< 0.52	< 0.78	< 0.85	< 0.54	4
4.037506	11.5	(10.1)	2.00 ± 0.40	< 2.31	< 1.91	< 0.35	< 0.34	5

*See Figure 1. For this object refer to the corresponding footnote to Table 7: here for Q1645+5520 the specific lengths and separation of observing runs become manifest simply as a mild broadening of the atmospheric emission and absorption lines.

- ^aC IV $\lambda 1551$ is blended with Si IV $\lambda 1394$ at $z = 3.468$ but $\lambda 1548$ is clear.
- ^bC IV $\lambda 1548$ has mild contamination by atmospheric line absorption but $\lambda 1551$ is clear.
- ^cC IV $\lambda 1551$ in component 1 has weak atmospheric line absorption but $\lambda 1548$ is clear.
- ^dC IV $\lambda 1551$ is blended with weak C II at $z = 4.024$ but $\lambda 1548$ is clear.
- ^eC IV $\lambda 1548$ is blended with weak C II at $z = 4.037$ but $\lambda 1551$ is clear. This system marks the start of a sequence of three weak C IV systems: $\lambda 1551$ blended with $\lambda 1548$ at $z = 3.348$ and $\lambda 1551$ of the latter system blended with $\lambda 1548$ at $z = 3.355$.
- ^fC IV $\lambda 1548$ is closely adjacent to weak Si IV $\lambda 1403$ at $z = 3.881$ and in components 1 and 2 contains weak atmospheric line emission but $\lambda 1551$ is clear. The values for Si IV are from $\lambda 1403$ which is outside the forest.
- ^gC IV $\lambda 1548$ in component 1 has strong contamination by atmospheric line absorption but $\lambda 1551$ is clear. Si IV $\lambda 1394$ in component 2 contains weak C IV $\lambda 1551$ at $z = 3.015$ but $\lambda 1403$ is clear.
- ^hC IV $\lambda 1551$ is contaminated by atmospheric line absorption and blended with Si IV $\lambda 1394$ at $z = 4.024$ but $\lambda 1548$ is sufficiently clear of interference for definition of the recorded components. Si IV $\lambda 1394$ is too contaminated by atmospheric line absorption to be useful and $\lambda 1403$ is masked by Si IV $\lambda 1394$ at $z = 3.544$.
- ⁱC IV $\lambda 1551$ is blended with Si IV $\lambda 1403$ at $z = 4.024$ but $\lambda 1548$ is clear. Si IV $\lambda 1394$ is partially blended with weak Si IV $\lambda 1403$ at $z = 3.514$ and components 3 and 4 include atmospheric line emission but $\lambda 1403$ is clear.
- ^jC IV $\lambda 1548$ has mild contamination by atmospheric line absorption but $\lambda 1551$ is clear. Si IV $\lambda 1403$ has strong interference by atmospheric line emission but $\lambda 1394$ is clear. C II is outside the forest; in component 4 it there is mild interference by atmospheric line emission.
- ^kC IV $\lambda 1551$ in components 9–11 is excluded by strong atmospheric line emission but here $\lambda 1548$ is clear, and additional mild atmospheric line absorption is present in both, but taken together good values are obtained for all components. C II in components 1 and 2 is masked by strong Si II $\lambda 1260$ at $z = 4.031$ and in further components overlaps with extended weak Si II in the same system but useful upper limits are obtained as listed.
- ^lC II in component 1 is too contaminated by atmospheric line emission to be useful.
- ^mSi IV $\lambda 1403$ is close in wavelength to C IV $\lambda 1551$ at $z = 3.322$ and the upper limit is from $\lambda 1394$.
- ⁿC II is obscured by C IV $\lambda 1548$ at $z = 3.193$.
- ^oThere is weak atmospheric line emission in both C IV doublet members but taken together the interference is not significant. Si IV $\lambda 1403$ is close in wavelength to C IV $\lambda 1548$ at $z = 3.421$ but $\lambda 1394$ is clear. C II in component 2 is excluded by weak atmospheric line absorption.
- ^pC IV $\lambda 1551$ is largely immersed in strong atmospheric line absorption and not used but $\lambda 1548$ is clear except for component 1 which is only mildly affected. Si IV $\lambda 1403$ has similar interference in component 1 and in 4 and 5 is rather noisy but $\lambda 1394$ is clear. Si II $\lambda 1260$ is outside the forest.
- ^qC IV $\lambda 1551$ has interference by strong line emission but $\lambda 1548$ is relatively clear and taken together the listed values are acceptable. Weak atmospheric line absorption occurs in component 1 of Si IV $\lambda 1394$, component 2 of $\lambda 1403$ and component 3 in both and the listed values are from the available complementary regions. C II is obscured by C IV $\lambda 1548$ at $z = 3.289$. Si II $\lambda 1260$ is too "noisy" to include.
- ^rC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 4.031$ but $\lambda 1548$ is clear of significant atmospheric interference and good values are obtained. Si IV $\lambda 1403$ is immersed in strong C IV $\lambda 1551$ at $z = 3.544$ while $\lambda 1394$ in components 1 and 2 is blended with C IV $\lambda 1551$ at $z = 3.514$ and also in component 1 is contaminated by atmospheric line absorption, but together good values are obtained for components 2–7. C II in components 1–4 is blended with C IV $\lambda 1551$ at $z = 3.322$ and in 7 with weak Si IV $\lambda 1394$ at $z = 3.811$ but acceptable values are obtained for all components. Si II $\lambda 1260$ is masked by Si IV $\lambda 1394$ at $z = 3.544$. N V is outside the forest.
- ^sThis complex system has strong C II and Si II and relatively weak related C IV in components 6–10: for these collectively a reasonable fit to the H I Lyman α damping wings is given by $\log N(\text{H I}) \sim 19.7$. Onward from component 12 C IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 4.024$ and in components 1 and 2 $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 4.037$ but taken together good values are obtained. Although Si IV has some contamination by atmospheric line absorption, good values are obtained for all components. C II is in a fully clear region. In the strong components Si II $\lambda 1260$ is mildly saturated but together with $\lambda 1304$ good values are obtained ($\lambda 1527$ is heavily contaminated by atmospheric line absorption); in components 12–17 weak $\lambda 1260$ is blended with weak C II at $z = 3.752$ but some useful upper limits are listed. All of N V is clear.
- ^tC IV $\lambda 1548$ in component 1 coincides with strong atmospheric line emission and in 5 encroaches on C IV $\lambda 1551$ at $z = 4.031$, while $\lambda 1551$ in components 2 and 3 also has interference from strong atmospheric line emission, but together good values are obtained. Si IV $\lambda 1394$ is partly contaminated by atmospheric line absorption but the values extracted are acceptable, while Si IV $\lambda 1403$ is too "noisy" to be useful. C II is blended with weak C IV $\lambda 1548$ at $z = 3.341$ but by including C IV $\lambda 1551$ useful values are obtained. All of N V is clear.

TABLE 9
HEAVY ELEMENT ABSORPTION LINES: Q1055+4611 $z_{em} = 4.15^*$

z	$b(C)$ km s^{-1}	$b(Si)$ km s^{-1}	$N(C \text{ IV})$ 10^{12}cm^{-2}	$N(Si \text{ IV})$ 10^{11}cm^{-2}	$N(C \text{ II})$ 10^{12}cm^{-2}	$N(Si \text{ II})$ 10^{11}cm^{-2}	$N(N \text{ V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.063 ^a								
3.061530	11.8	...	11.7 ± 0.5	...	...	...	...	1
3.062074	5.1	...	3.92 ± 0.33	...	...	...	...	2
3.062485	8.5	...	85.8 ± 1.5	...	...	...	...	3
3.062607	5.1	...	17.4 ± 0.8	...	...	...	...	4
3.063773	11.3	...	7.72 ± 0.49	...	...	...	...	5
3.090 ^b								
3.090376	21.3	...	1.89 ± 0.28	...	...	...	...	1
3.122								
3.121821	9.7	...	3.06 ± 0.17	...	...	...	...	1
3.122077	19.5	...	1.99 ± 0.30	...	...	...	...	2
3.122197	4.2	...	12.9 ± 0.2	...	...	...	...	3
3.122825	17.8	...	0.80 ± 0.18	...	...	...	...	4
3.154 ^c								
3.153131	26.9	...	1.11 ± 0.50	...	...	...	...	1
3.153408	13.2	...	2.44 ± 0.36	...	...	...	...	2
3.154130	28.7	...	1.44 ± 0.48	...	...	...	...	3
3.154489	16.0	...	2.83 ± 0.40	...	...	...	...	4
3.155057	16.5	...	2.28 ± 0.35	...	...	...	...	5
3.167								
3.163730	7.1	...	3.68 ± 0.22	...	...	...	...	1
3.163925	7.6	...	3.92 ± 0.23	...	...	...	...	2
3.165066	12.4	...	2.68 ± 0.25	...	...	...	...	3
3.165533	4.6	...	1.17 ± 0.17	...	...	...	...	4
3.166536	29.1	...	6.33 ± 0.41	...	...	...	...	5
3.166717	7.1	...	6.39 ± 0.24	...	...	...	...	6
3.167199	8.4	...	9.48 ± 0.22	...	...	...	...	7
3.167448	7.3	...	1.98 ± 0.18	...	...	...	...	8
3.168484	8.1	...	3.73 ± 0.21	...	...	...	...	9
3.168668	7.2	...	5.53 ± 0.23	...	...	...	...	10
3.168806	5.0	...	8.57 ± 0.24	...	...	...	...	11
3.169067	11.5	...	4.87 ± 0.22	...	...	...	...	12
3.169356	12.7	...	2.72 ± 0.22	...	...	...	...	13
3.228 ^d								
3.227567	9.8	...	11.3 ± 0.4	...	...	...	...	1
3.227794	10.2	...	5.61 ± 0.38	...	...	...	...	2
3.228220	21.5	...	2.87 ± 0.51	...	...	...	...	3
3.234 ^e								
3.233204	6.1	...	3.34 ± 0.42	...	...	...	...	1
3.233413	37.7	...	5.88 ± 1.07	...	...	...	...	2
3.233769	11.5	...	22.8 ± 0.7	...	...	...	...	3
3.235253	16.1	...	3.79 ± 0.38	...	...	...	...	4
3.238								
3.236618	13.2	...	16.7 ± 0.6	...	...	...	...	1
3.236759	4.1	...	17.1 ± 1.1	...	...	...	...	2
3.236866	6.6	...	24.0 ± 1.0	...	...	...	...	3
3.237038	11.9	...	16.8 ± 0.6	...	...	...	...	4
3.237794	9.1	...	1.34 ± 0.37	...	...	...	...	5
3.238040	9.2	...	10.1 ± 0.4	...	...	...	...	6
3.238369	9.9	...	39.8 ± 0.8	...	...	...	...	7
3.238679	9.9	...	43.5 ± 0.9	...	...	...	...	8
3.238910	8.1	...	17.7 ± 0.6	...	...	...	...	9
3.239162	9.9	...	10.4 ± 0.4	...	...	...	...	10
3.239429	8.6	...	9.49 ± 0.44	...	...	...	...	11
3.239661	13.1	...	5.14 ± 0.48	...	...	...	...	12
3.269								
3.268610	11.6	...	4.45 ± 0.19	...	...	...	...	1
3.269033	27.5	...	2.47 ± 0.27	...	...	...	...	2

TABLE 9—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.317^f								
3.314915	2.9	(1.9)	0.83 ± 0.18	...	...	< 2.37	...	1
3.315923	6.4	(5.2)	6.89 ± 0.27	...	...	< 2.84	...	2
3.316131	5.2	(4.3)	25.6 ± 0.6	...	...	< 3.47	...	3
3.316262	4.6	(3.7)	13.8 ± 0.4	...	...	< 2.95	...	4
3.316486	2.9	(1.9)	1.66 ± 0.20	...	...	3.66 ± 2.43	...	5
3.316717	3.3	(2.2)	1.20 ± 0.20	...	...	< 4.07	...	6
3.316851	7.1	(5.7)	1.28 ± 0.42	...	...	344 ± 13	...	7
3.317070	(17)	16.4	< 1.38	...	...	70.1 ± 26.0	...	8
3.317183	10.7	(9.1)	3.92 ± 0.76	...	...	986 ± 46	...	9
3.317346	5.8	(4.4)	5.43 ± 0.32	...	...	262 ± 16	...	10
3.317476	6.0	(5.5)	4.96 ± 0.29	...	...	44.1 ± 4.4	...	11
3.317710	11.8	(10.4)	10.5 ± 0.4	...	...	19.8 ± 4.6	...	12
3.317878	(7)	5.6	< 0.34	...	...	21.0 ± 4.2	...	13
3.318006	11.1	(9.7)	8.33 ± 0.37	...	...	< 6.78	...	14
3.318554	13.4	(12.3)	3.38 ± 0.28	...	...	< 4.47	...	15
3.318961	9.4	(7.7)	1.90 ± 0.23	...	...	< 3.28	...	16
3.319446	5.7	(4.7)	1.68 ± 0.21	...	...	< 2.69	...	17
3.332^g								
3.331308	6.6	...	0.69 ± 0.17	...	...	...	...	1
3.331784	7.1	...	0.99 ± 0.16	...	...	...	...	2
3.332094	7.6	...	1.53 ± 0.18	...	...	...	...	3
3.332283	6.7	...	0.76 ± 0.18	...	...	...	...	4
3.332733	7.4	...	0.43 ± 0.18	...	...	...	...	5
3.359^h								
3.358324	10.3	...	1.25 ± 0.24	...	...	...	...	1
3.358781	15.4	...	5.23 ± 0.31	...	...	...	...	2
3.359286	18.1	...	7.89 ± 0.32	...	...	...	...	3
3.406ⁱ								
3.404510	15.1	...	1.93 ± 0.39	...	...	...	...	1
3.404899	4.2	...	1.42 ± 0.25	...	...	...	...	2
3.405261	12.4	...	7.54 ± 0.40	...	...	...	...	3
3.405677	16.4	...	5.83 ± 0.42	...	...	...	...	4
3.406767	20.0	...	1.83 ± 0.36	...	...	...	...	5
3.477^j								
3.477253	9.6	(7.9)	8.39 ± 0.46	16.5 ± 0.6	...	...	...	1
3.521^k								
3.520863	11.6	(10.2)	5.34 ± 0.23	< 1.56	...	...	...	1
3.521115	7.2	(6.1)	2.28 ± 0.19	< 1.44	...	...	...	2
3.533^l								
3.530522	7.3	(5.8)	3.81 ± 0.22	8.68 ± 0.78	...	...	...	1
3.530699	5.2	(3.6)	3.15 ± 0.34	14.4 ± 1.2	...	...	...	2
3.530866	15.6	(14.6)	20.8 ± 0.6	92.4 ± 1.9	...	...	...	3
3.531125	9.1	(6.4)	38.7 ± 1.1	78.9 ± 2.2	...	...	...	4
3.531322	6.3	(5.7)	19.6 ± 2.0	215 ± 11	...	43.0 ± 15.4	...	5
3.531380	7.6	(5.8)	17.4 ± 1.5	< 4.19	...	...	...	6
3.531594	27.8	(27.3)	35.3 ± 0.8	55.1 ± 2.3	...	...	...	7
3.532027	13.8	(12.7)	12.9 ± 0.5	4.31 ± 1.38	...	...	...	8
3.531908	5.1	(4.6)	2.18 ± 0.38	13.0 ± 1.1	...	...	...	9
3.532459	15.8	(14.8)	7.21 ± 0.30	21.6 ± 1.1	...	...	...	10
3.532985	8.7	(5.3)	2.80 ± 0.37	18.8 ± 1.2	...	...	...	11
3.533056	4.1	(3.8)	1.72 ± 0.30	1.41 ± 0.97	...	...	...	12
3.533513	20.7	(19.9)	2.07 ± 0.31	5.88 ± 1.16	...	...	...	13
3.534188	15.6	(14.6)	5.78 ± 0.34	1.66 ± 1.08	...	...	...	14
3.534422	8.5	(7.0)	15.1 ± 0.4	24.4 ± 1.0	...	...	...	15
3.534598	4.3	(3.8)	1.70 ± 0.22	8.72 ± 0.73	...	...	...	16
3.534792	6.0	(4.7)	6.78 ± 0.69	4.14 ± 2.41	...	...	...	17

TABLE 9—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.535123	11.3	(9.9)	3.26 ± 0.25	< 0.98	...	...	...	18
3.535494	7.4	(6.4)	67.7 ± 2.0	56.5 ± 1.4	...	...	...	19
3.535615	3.1	(2.4)	19.4 ± 3.5	< 0.95	...	...	...	20
3.535714	11.1	(9.6)	26.9 ± 0.6	14.4 ± 1.2	...	...	...	21
3.644 ^m								
3.644101	3.7	(2.4)	7.49 ± 0.46	5.96 ± 0.46	...	...	...	1
3.646 ⁿ								
3.645768	5.4	(4.7)	1.98 ± 0.30	< 0.53	...	...	...	1
3.645995	4.2	(3.2)	2.16 ± 0.34	2.17 ± 0.47	...	...	...	2
3.754 ^o								
3.753044	13.3	(12.2)	7.04 ± 1.05	< 1.11	< 0.52	...	...	1
3.753395	3.1	(2.0)	1.63 ± 0.66	< 0.65	< 0.29	...	...	2
3.753693	3.4	(2.4)	11.2 ± 2.6	10.4 ± 0.9	< 0.22	...	...	3
3.753847	14.1	(13.0)	64.6 ± 3.2	19.3 ± 1.3	< 0.39	...	...	4
3.754563	12.5	(11.2)	13.5 ± 1.0	8.41 ± 1.23	< 0.28	...	...	5
3.789 ^p								
3.787638	9.6	(7.9)	3.48 ± 0.43	< 1.47	< 0.29	...	...	1
3.788301	5.0	(4.0)	0.97 ± 0.32	< 1.38	< 0.24	...	...	2
3.789095	4.1	(2.7)	0.91 ± 0.30	< 1.66	< 0.44	...	...	3
3.789357	5.6	(4.1)	0.62 ± 0.32	< 1.28	< 0.68	...	...	4
3.822								
3.822015	9.9	(8.2)	3.82 ± 0.57	< 0.66	< 0.52	...	...	1
3.826 ^q								
3.824474	24.5	(23.9)	9.64 ± 1.05	8.51 ± 1.15	< 0.71	...	...	1
3.824886	8.8	(7.4)	6.96 ± 0.91	21.8 ± 0.9	< 0.53	...	...	2
3.825085	12.7	(11.5)	15.3 ± 1.0	31.1 ± 1.1	3.41 ± 0.60	...	...	3
3.825562	10.6	(9.1)	11.8 ± 1.0	37.3 ± 1.1	< 0.74	...	...	4
3.825680	4.0	(3.2)	3.09 ± 0.81	56.9 ± 2.0	5.07 ± 0.51	7.20 ± 0.72	...	5
3.825841	6.2	(5.3)	6.72 ± 0.93	64.7 ± 1.5	9.60 ± 0.56	16.30 ± 0.73	...	6
3.826099	15.7	(14.7)	36.9 ± 1.7	97.5 ± 1.6	1.03 ± 0.77	...	...	7
3.826380	10.6	(9.4)	8.90 ± 1.57	3.01 ± 1.17	< 0.70	...	...	8
3.826596	11.3	(9.9)	15.9 ± 1.5	52.2 ± 1.3	1.48 ± 0.71	...	...	9
3.826796	6.1	(5.0)	6.65 ± 1.21	31.1 ± 1.1	< 0.60	...	...	10
3.826924	8.5	(7.0)	9.42 ± 0.99	11.6 ± 0.9	< 0.56	...	...	11
3.850 ^r								
3.848913	4.8	(3.7)	< 0.81	8.09 ± 0.83	0.74 ± 0.25	...	...	1
3.849088	4.2	(2.8)	1.80 ± 0.61	13.4 ± 0.9	6.00 ± 0.30	...	...	2
3.849375	11.8	(10.4)	7.68 ± 0.91	27.0 ± 1.3	3.03 ± 0.35	...	...	3
3.849792	8.5	(7.1)	3.06 ± 0.89	23.5 ± 1.4	1.92 ± 0.41	...	...	4
3.849910	3.7	(2.4)	< 0.71	2.51 ± 1.15	1.21 ± 0.31	...	...	5
3.851317	15.9	(14.9)	7.85 ± 1.06	6.17 ± 1.60	< 0.40	...	...	6
3.884								
3.884106	6.6	(5.3)	4.29 ± 0.59	4.20 ± 1.15	< 1.18	...	...	1
3.884255	8.4	(7.1)	12.5 ± 0.7	11.8 ± 1.3	< 1.08	...	...	2
3.884492	8.0	(7.1)	1.39 ± 0.46	5.73 ± 1.20	< 0.82	...	...	3
3.934 ^s								
3.932549	10.8	(9.4)	6.86 ± 1.59	14.0 ± 0.8	< 0.60	...	...	1
3.932807	4.8	(4.0)	7.31 ± 2.06	< 1.17	< 0.43	...	...	2
3.932907	10.2	(8.6)	6.02 ± 1.60	9.92 ± 1.14	< 0.58	...	...	3
3.933551	15.5	(14.5)	14.6 ± 1.9	4.73 ± 1.12	< 0.47	...	...	4
3.934134	12.8	(11.6)	9.08 ± 1.44	24.1 ± 1.6	< 0.52	...	...	5
3.934314	8.4	(6.9)	8.06 ± 1.20	23.0 ± 1.1	< 0.53	...	...	6
3.934635	8.2	(6.9)	7.46 ± 0.88	16.4 ± 0.8	0.44 ± 0.34	...	...	7

*See Figure 1. For this object refer to the corresponding footnote to Table 8: here for Q1055+4611 the specific lengths and separation of observing runs again become manifest as a mild broadening of the atmospheric emission and absorption lines. Furthermore, in addition to the normal sky subtraction procedure which is common to all objects, the atmospheric line absorption is here "divided out" by use of a related spectrum of a calibration object nearby on the sky. This gives the advantage of restoring the QSO spectrum to a normalized continuum and directly makes available a fraction more spectral coverage without the complication of unraveling the atmospheric absorp-

tion. Whether so processed or not, information is of course unavoidably compromised through the intrinsically enhanced noise and ultimately obscured in the most heavily absorbed regions where these lines are saturated.

^aC IV $\lambda 1548$ is blended with Fe II $\lambda 1608$ at $z = 2.912$ but $\lambda 1551$ is relatively clear with effectively only minor interference by atmospheric line absorption and emission.

^bC IV $\lambda 1551$ contains very weak C II at $z = 3.754$ but $\lambda 1548$ is clear.

^cC IV $\lambda 1551$ is blended with C II at $z = 3.826$ but $\lambda 1548$ is clear.

^dC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 3.234$ but $\lambda 1548$ is clear although with mild interference by atmospheric line absorption and emission.

^eC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 3.228$ but $\lambda 1551$ is clear.

^fThis is a complex system with very strong Si II $\lambda 1527$ ($\lambda 1260$ is in the forest) and relatively weak related C IV in components 7–10: for these, $\log N(\text{H I})$ totalling ~ 20.3 gives a reasonable fit to the H I Lyman α damping wings, verging on the “damped Lyman α ” classification. Both of C IV $\lambda\lambda 1548, 1551$ are partially blended with Mg II $\lambda 2804$ in a strong, extended system at $z = 1.386$ but taken together good values are obtained. Si b -values here relate to Si II.

^gC IV $\lambda 1551$ is blended with weak Si IV $\lambda 1403$ at $z = 3.789$ but $\lambda 1548$ is clear.

^hC IV $\lambda 1551$ is blended with Si IV $\lambda 1394$ at $z = 3.850$ but $\lambda 1548$ is clear.

ⁱC IV $\lambda 1551$ has partial interference by atmospheric line emission but $\lambda 1548$ is clear.

^jC IV $\lambda 1551$ is blended with strong Fe II $\lambda 1608$ at $z = 3.317$ but $\lambda 1548$ is relatively clear. Si IV $\lambda 1403$ is outside the forest and not significantly affected by mild atmospheric line absorption which is present.

^kSi IV $\lambda 1394$ is heavily contaminated by atmospheric line emission and also is blended with C IV $\lambda 1551$ at $z = 3.063$ but $\lambda 1403$ is clear.

^lThis is a highly complex system. In Si IV $\lambda 1403$ there is an unidentified interloper at observed wavelength $\lambda 6359.9$ near component 13, but in a relatively clear region within the complex, and Si IV $\lambda 1394$ is clear. Si II $\lambda 1260$ is in the forest; Si II $\lambda 1527$ is generally relatively weak and partially blended with much stronger Si IV $\lambda 1403$ at $z = 3.934$ and, with the exception of the strong component 5, yields only upper limits which are too high to be useful.

^mC IV $\lambda 1551$ has strong atmospheric line absorption but $\lambda 1548$ is clear. Si IV $\lambda 1394$ resides in C II at $z = 3.850$ but $\lambda 1403$ is clear although in a rather noisy region.

ⁿC IV $\lambda 1548$ has strong atmospheric line absorption but $\lambda 1551$ is clear. Si IV $\lambda 1403$ is in a noisy region and not used but $\lambda 1394$ is clear.

^oC IV $\lambda 1548$ near component 4 and $\lambda 1551$ in component 1 have strong atmospheric line emission and both are in a rather noisy region, but taken together acceptable values are obtained in all components. Si IV $\lambda 1403$ in component 5 is blended with Mg II $\lambda 2796$ at $z = 1.386$ but $\lambda 1394$ is clear. C II is outside the forest; components 1 and 2 are blended with weak C IV $\lambda 1551$ at $z = 3.090$ but taken with $\lambda 1548$ reasonable upper limits are obtained.

^pSi IV $\lambda 1394$ is masked by very strong Mg II $\lambda 2796$ at $z = 1.386$ and $\lambda 1403$ in components 2–4 is blended with weak C IV $\lambda 1551$ at $z = 3.332$, but together with $\lambda 1548$ in that system reasonable upper limits are obtained. C II in component 4 is close in wavelength to C IV $\lambda 1551$ at $z = 3.122$ but the upper limit is useful.

^qC IV $\lambda 1551$ has significant interference by atmospheric line emission but $\lambda 1548$ is relatively clear and together good values are obtained. C II is partially blended with C IV $\lambda 1551$ at $z = 3.154$ but taken with $\lambda 1548$ in that system good values are obtained. Si II $\lambda 1260$ is in the forest but the two narrow and strong components 5 and 6 are in a clear region and give good values consistent with the weak $\lambda 1527$.

^rC IV is in a rather noisy region. Si IV $\lambda 1394$ includes weaker C IV $\lambda 1551$ at $z = 3.359$ but $\lambda 1403$ is clear. C II contains narrow Si IV $\lambda 1394$ at $z = 3.644$ which however is in a clear part of the complex.

^sC IV is in a region with very strong atmospheric line absorption but over the doublet the values obtained are acceptable. Si IV $\lambda 1403$ contains very weak Si II $\lambda 1527$ at $z = 3.533$ but $\lambda 1394$ is relatively clear and good values are obtained.

TABLE 10
HEAVY ELEMENT ABSORPTION LINES: Q2237-0607 $z_{em} = 4.56^*$

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.433 ^a								
3.432137	18.1	...	1.38 ± 0.22	...	...	...	...	1
3.432510	12.5	...	5.06 ± 0.19	...	...	...	...	2
3.432872	15.4	...	4.17 ± 0.20	...	...	...	...	3
3.433346	14.4	...	8.11 ± 0.20	...	...	...	...	4
3.433767	15.7	...	2.27 ± 0.20	...	...	...	...	5
3.434190	5.9	...	0.38 ± 0.12	...	...	...	...	6
3.448								
3.447979	6.1	...	1.78 ± 0.14	...	...	...	...	1
3.454								
3.454071	6.6	...	1.88 ± 0.15	...	...	...	...	1
3.482 ^b								
3.480721	6.1	...	5.83 ± 0.33	...	...	...	...	1
3.480900	7.2	...	1.57 ± 0.39	...	...	...	...	2
3.481150	3.7	...	0.73 ± 0.21	...	...	...	...	3
3.481795	3.2	...	0.58 ± 0.21	...	...	...	...	4
3.482812	8.4	...	2.35 ± 0.51	...	...	...	...	5
3.591								
3.590142	9.0	...	0.98 ± 0.19	...	...	...	...	1
3.591022	14.4	...	3.81 ± 0.24	...	...	...	...	2
3.604 ^c								
3.603319	6.2	...	0.78 ± 0.25	...	...	...	...	1
3.603784	8.5	...	2.20 ± 0.21	...	...	...	...	2
3.604063	9.3	...	0.44 ± 0.18	...	...	...	...	3
3.604742	21.6	...	4.87 ± 0.25	...	...	...	...	4
3.605166	9.7	...	3.18 ± 0.22	...	...	...	...	5
3.605526	5.0	...	0.93 ± 0.16	...	...	...	...	6
3.627 ^d								
3.626887	17.7	...	7.42 ± 0.86	...	...	...	...	1
3.626972	7.8	...	5.65 ± 0.65	...	...	...	...	2
3.681 ^e								
3.681058	15.6	...	3.29 ± 0.40	...	...	...	...	1
3.681358	10.4	...	1.56 ± 0.24	...	...	...	...	2
3.681789	9.7	...	0.91 ± 0.33	...	...	...	...	3
3.748 ^f								
3.746527	9.4	...	4.92 ± 0.37	...	...	...	...	1
3.746813	8.8	...	1.41 ± 0.34	...	...	...	...	2
3.748577	10.5	...	3.14 ± 0.38	...	...	...	...	3
3.756 ^g								
3.756282	6.1	...	1.56 ± 0.31	...	...	...	...	1
3.794								
3.793849	17.1	...	4.78 ± 0.32	...	...	...	...	1
3.794448	26.0	...	1.45 ± 0.40	...	...	...	...	2
3.811 ^h								
3.808354	28.0	...	4.17 ± 0.63	...	...	...	...	1
3.809181	9.4	...	1.60 ± 0.38	...	...	...	...	2
3.810379	6.7	...	4.47 ± 0.38	...	...	...	...	3
3.810655	7.1	...	1.44 ± 0.36	...	...	...	...	4
3.810928	13.1	...	2.62 ± 0.48	...	...	...	...	5
3.811434	9.3	...	2.98 ± 0.39	...	...	...	...	6
3.811845	7.6	...	0.52 ± 0.34	...	...	...	...	7
3.812758	16.9	...	3.42 ± 0.50	...	...	...	...	8
3.813257	5.9	...	1.02 ± 0.32	...	...	...	...	9
3.825 ⁱ								
3.824580	8.6	(7.0)	4.08 ± 0.63	17.3 ± 0.9	...	...	...	1
3.824747	7.2	(4.7)	2.80 ± 0.98	1.64 ± 0.72	...	...	...	2

TABLE 10—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
3.832 ^j								
3.829879	28.5	...	17.4 ± 2.1	...	...	...	...	1
3.830918	13.8	...	8.88 ± 1.31	...	...	...	...	2
3.831427	15.0	(13.9)	17.4 ± 1.5	42.4 ± 37.6	...	...	...	3
3.831933	12.8	(11.5)	41.7 ± 1.9	108 ± 33	...	...	...	4
3.832314	12.4	(11.1)	5.18 ± 1.28	39.9 ± 18.4	...	...	...	5
3.833277	8.3	...	4.51 ± 1.27	...	...	...	...	6
3.978 ^k								
3.976775	9.1	(7.3)	1.80 ± 0.52	< 0.93	...	...	...	1
3.977090	5.2	(3.4)	1.39 ± 0.44	< 0.72	...	...	...	2
3.977349	8.1	(6.6)	3.07 ± 0.61	4.99 ± 1.97	...	...	...	3
3.977591	15.9	(14.9)	3.47 ± 0.73	< 1.86	...	...	...	4
3.978222	18.4	(17.5)	10.2 ± 0.7	6.03 ± 1.13	...	...	...	5
3.978890	8.6	(6.8)	1.85 ± 0.64	6.27 ± 1.11	...	...	...	6
3.979087	19.4	(18.6)	5.10 ± 0.89	< 1.53	...	...	...	7
4.030								
4.028668	10.5	(9.1)	2.19 ± 0.42	1.23 ± 0.87	...	...	...	1
4.029160	25.1	(24.5)	2.45 ± 0.61	< 1.34	...	...	...	2
4.029586	9.4	(7.8)	4.56 ± 0.40	4.87 ± 0.79	...	...	...	3
4.030407	7.4	(6.6)	0.76 ± 0.35	< 0.69	...	...	...	4
4.031057	17.0	(16.1)	5.37 ± 0.54	< 1.03	...	...	...	5
4.080 ^l								
4.078068	7.8	(6.3)	1.66 ± 0.57	1.49 ± 1.01	3.10 ± 0.33	...	...	1
4.078373	3.6	(2.5)	< 1.59	< 2.01	31.2 ± 3.7	18.1 ± 10.0	...	2
4.078401	9.1	(7.2)	3.94 ± 1.86	4.75 ± 2.69	55.2 ± 6.9	78.5 ± 12.5	...	3
4.078669	9.8	(8.2)	1.03 ± 0.84	5.36 ± 1.40	109 ± 4	164 ± 7	...	4
4.078874	8.4	(6.6)	< 0.81	12.5 ± 1.3	66.1 ± 4.5	92.5 ± 6.2	...	5
4.079041	3.3	(2.2)	1.06 ± 0.51	2.88 ± 0.92	16.9 ± 2.4	23.8 ± 4.2	...	6
4.079178	4.3	(3.2)	1.39 ± 0.56	5.69 ± 1.02	39.4 ± 1.7	74.1 ± 5.0	...	7
4.079364	8.8	(7.1)	5.36 ± 0.79	17.9 ± 1.3	< 3.46	10.3 ± 4.2	...	8
4.079609	7.5	(5.9)	18.0 ± 1.7	16.0 ± 2.6	4.65 ± 1.24	11.4 ± 5.5	...	9
4.079721	9.2	(7.4)	13.4 ± 1.8	42.1 ± 2.5	2.76 ± 0.96	...	...	10
4.079979	10.6	(9.1)	9.12 ± 1.03	45.8 ± 1.8	35.0 ± 1.3	64.7 ± 6.1	...	11
4.080205	8.1	(6.5)	3.01 ± 0.80	28.9 ± 1.5	277 ± 15	468 ± 17	...	12
4.080359	3.4	(2.3)	< 0.93	24.0 ± 2.8	28.5 ± 6.8	87.2 ± 10.7	...	13
4.080462	6.6	(5.4)	3.04 ± 0.87	31.7 ± 2.6	39.3 ± 1.5	61.1 ± 6.0	...	14
4.080655	7.4	(5.8)	1.70 ± 0.63	10.9 ± 1.2	69.0 ± 1.7	111 ± 6	...	15
4.080852	4.9	(3.9)	1.35 ± 0.55	7.28 ± 1.03	281 ± 18	385 ± 189	...	16
4.081019	7.4	(6.0)	< 0.80	4.13 ± 1.22	7.26 ± 0.56	14.3 ± 4.8	...	17
4.081189	8.4	(6.9)	< 0.92	3.85 ± 1.22	2.05 ± 0.29	...	...	18
4.081509	9.7	(8.1)	3.26 ± 0.65	4.17 ± 1.12	0.34 ± 0.20	...	...	19
4.086 ^m								
4.085645	12.1	(10.8)	3.31 ± 0.68	6.03 ± 1.26	< 0.21	...	...	1
4.089 ⁿ								
4.088900	7.8	(6.9)	6.27 ± 0.78	3.54 ± 1.01	0.43 ± 0.19	...	...	1
4.094 ^o								
4.093972	16.0	(15.1)	6.50 ± 0.77	4.68 ± 1.42	< 0.34	...	...	1
4.200 ^p								
4.199860	9.2	(7.4)	1.38 ± 0.68	< 1.16	...	...	...	1
4.200502	12.9	(11.7)	11.6 ± 0.9	6.22 ± 1.53	...	...	...	2
4.200809	8.4	(6.8)	6.77 ± 0.87	< 1.06	< 0.12	...	...	3
4.231 ^q								
4.229886	8.3	(6.7)	0.79 ± 0.41	< 2.30	< 0.38	...	...	1
4.230182	5.8	(5.1)	3.16 ± 0.41	< 1.65	...	...	...	2
4.230435	7.9	(6.2)	15.0 ± 0.7	4.66 ± 0.78	...	...	...	3
4.230771	7.8	(6.1)	3.06 ± 0.45	< 0.73	...	...	...	4
4.231091	5.8	(4.9)	3.06 ± 0.43	< 0.68	< 0.29	...	...	5

TABLE 10—*Continued*

z	$b(\text{C})$ km s^{-1}	$b(\text{Si})$ km s^{-1}	$N(\text{C IV})$ 10^{12}cm^{-2}	$N(\text{Si IV})$ 10^{11}cm^{-2}	$N(\text{C II})$ 10^{12}cm^{-2}	$N(\text{Si II})$ 10^{11}cm^{-2}	$N(\text{N V})$ 10^{12}cm^{-2}	n
1	2	3	4	5	6	7	8	9
4.231385	8.9	(7.2)	1.23 ± 0.47	< 0.79	< 0.36	...	...	6
4.231826	6.5	(5.3)	1.15 ± 0.37	< 0.86	< 0.47	...	...	7
4.239 ^r								
4.237075	8.4	(6.8)	3.19 ± 0.44	< 1.31	< 0.38	...	...	1
4.238095	7.2	(4.7)	1.10 ± 0.40	< 0.73	< 0.48	...	...	2
4.239683	13.5	(12.4)	2.98 ± 0.64	29.9 ± 1.4	3.61 ± 0.57	...	...	3
4.239891	4.1	(3.0)	1.38 ± 0.42	6.40 ± 0.90	< 0.50	...	...	4
4.240122	10.5	(9.0)	3.29 ± 0.54	10.2 ± 1.0	< 0.45	...	...	5
4.247 ^s								
4.245677	7.0	(5.8)	1.16 ± 0.52	3.61 ± 1.01	< 0.37	...	...	1
4.246104	3.1	(2.1)	3.38 ± 0.56	< 0.77	< 0.39	...	...	2
4.247022	29.2	(28.7)	12.2 ± 1.5	11.6 ± 3.0	< 0.96	...	...	3
4.247807	21.2	(20.4)	9.09 ± 1.02	25.3 ± 2.1	< 0.72	...	...	4
4.286 ^t								
4.284727	10.1	(8.5)	1.30 ± 0.71	5.78 ± 1.58	< 0.54	...	...	1
4.285258	8.5	(7.0)	7.82 ± 0.93	18.4 ± 1.5	< 0.49	...	...	2
4.285650	10.4	(8.8)	10.3 ± 1.3	46.2 ± 2.0	< 0.81	...	...	3
4.286004	14.4	(13.3)	6.00 ± 4.07	13.6 ± 2.1	< 0.70	...	...	4
4.286205	3.9	(2.8)	5.60 ± 1.44	< 1.24	< 0.50	...	...	5
4.286412	13.4	(12.2)	5.97 ± 0.99	< 2.76	< 0.70	...	...	6
4.361 ^u								
4.359466	15.3	(14.3)	11.5 ± 0.9	55.8 ± 4.6	1.14 ± 0.58	< 0.96	...	1
4.359949	14.4	(13.3)	17.6 ± 1.6	68.6 ± 3.6	< 0.69	< 3.00	...	2
4.360144	5.8	(4.6)	8.50 ± 1.15	50.9 ± 3.8	1.42 ± 0.45	2.03 ± 0.49	...	3
4.360303	4.4	(3.5)	4.48 ± 0.91	71.3 ± 5.1	3.68 ± 0.46	4.96 ± 0.54	...	4
4.360496	9.5	(7.8)	29.6 ± 1.2	34.2 ± 2.3	< 0.76	< 0.66	...	5
4.360899	6.4	(5.2)	14.7 ± 0.7	34.0 ± 2.0	1.16 ± 0.41	< 0.44	...	6
4.361351	10.2	(8.7)	5.57 ± 1.37	< 7.27	< 0.90	< 0.41	...	7
4.361474	7.7	(5.3)	3.56 ± 1.80	65.9 ± 6.8	3.29 ± 0.78	1.66 ± 0.29	...	8
4.361758	13.7	(10.2)	13.5 ± 1.2	161 ± 9	12.0 ± 0.7	10.2 ± 0.4	...	9
4.362331	9.9	(8.2)	9.02 ± 0.73	37.8 ± 2.5	3.05 ± 0.59	0.74 ± 0.40	...	10
4.362589	10.4	(8.9)	13.0 ± 0.9	90.4 ± 4.1	19.2 ± 0.8	18.6 ± 0.4	...	11
4.362803	6.9	(5.7)	2.40 ± 0.75	65.9 ± 4.8	8.78 ± 0.69	9.98 ± 0.32	...	12
4.363034	22.4	(21.7)	14.5 ± 1.1	15.9 ± 4.5	< 1.09	...	...	13
4.389 ^v								
4.388714	7.2	(5.7)	3.59 ± 0.82	...	< 0.56	< 0.33	...	1
4.389280	3.7	(2.4)	0.90 ± 0.48	< 3.91	< 0.45	< 0.17	...	2
4.390043	6.1	(5.2)	2.78 ± 1.11	< 3.01	< 0.56	< 0.21	...	3

*See Figure 1. For this object refer to the corresponding footnote to Table 9: here for Q2237-0607 the atmospheric line absorption is treated similarly; and the specific lengths and separation of observing runs again become manifest as a mild broadening of the atmospheric emission and absorption lines.

^aC IV $\lambda 1551$ has mild interference by atmospheric line absorption but $\lambda 1548$ is clear.

^bC IV $\lambda 1548$ is blended with weak Si IV $\lambda 1394$ at $z = 3.978$ and weak C II at $z = 4.200$ and also has mild interference by atmospheric line absorption while $\lambda 1551$ has both absorption and emission, but taken together with both the Si IV doublet members at $z = 3.978$ good values are obtained.

^cC IV $\lambda 1548$ is partially blended with Si IV $\lambda 1403$ at $z = 4.080$ while $\lambda 1551$ in component 1 is blended with Si IV $\lambda 1403$ at $z = 4.089$ but together acceptable values are obtained.

^dC IV $\lambda 1551$ has mild interference by atmospheric line absorption but $\lambda 1548$ is clear.

^eC IV $\lambda 1548$ has interference by both atmospheric line absorption and emission while $\lambda 1551$ has absorption alone but taken together acceptable values are obtained.

^fC IV $\lambda 1548$ is blended with Si IV $\lambda 1403$ at $z = 4.239$ and $\lambda 1551$ is blended with Si IV $\lambda 1403$ at $z = 4.247$ and C IV $\lambda 1548$ at $z = 3.756$, and both have some interference by atmospheric line absorption and emission, but taking all together acceptable values are obtained.

^gC IV $\lambda 1548$ is blended with $\lambda 1551$ at $z = 3.748$ but $\lambda 1551$ is clear.

^hC IV $\lambda 1551$ in components 8 and 9 is mildly affected by atmospheric line emission but $\lambda 1548$ is clear. This is

a weak extended system and may represent possibly three separate close regions.

ⁱC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 3.832$ and heavily contaminated by atmospheric line emission and not used; $\lambda 1548$ is blended with component 1 in Si IV $\lambda 1394$ at $z = 4.361$ but good values are obtained by use of both Si IV doublet members of that system. Si IV $\lambda 1394$ is in the forest but $\lambda 1403$ is clear.

^jC IV $\lambda 1548$ is partially blended with Al III $\lambda 1855$ at $z = 3.032$ and strongly contaminated by atmospheric line emission while $\lambda 1551$ is clear of this except in component 6 but together with Al III $\lambda 1863$, itself blended with very weak Si IV $\lambda 1394$ at $z = 4.389$, good values are obtained for all components. Si IV $\lambda 1403$ is outside the forest and immersed in very strong C II $\lambda 1335$ at $z = 4.080$ but with the help of corresponding C II $\lambda 1036$, partially available in the forest, the values obtained are useful indicators despite the large relative uncertainties.

^kC IV $\lambda 1551$ has strong contamination by atmospheric line emission but $\lambda 1548$ is clear although in a rather noisy region. Si IV $\lambda 1394$ is blended with C IV $\lambda 1548$ at $z = 3.482$ and weak C II at $z = 4.200$ while $\lambda 1403$ is partially blended with very weak C II at $z = 4.231$ but together acceptable values are obtained.

^lThis is a complex system with C II and Si II very strong and C IV relatively weak in many of the components: collectively $\log N(\text{H I}) \sim 20.3$ gives a good fit to the outer parts of the H I Lyman α damping wings, at the “damped Lyman α ” classification. C IV $\lambda 1548$ in component 2 is contaminated by atmospheric line emission while $\lambda 1551$ in component 14 is blended with C IV $\lambda 1548$ at $z = 4.089$ but together good values are obtained. Si IV $\lambda 1403$ is blended with C IV $\lambda 1548$ at $z = 3.604$ but $\lambda 1394$ is clear. C II $\lambda 1335$, outside the forest, contains much weaker Si IV $\lambda 1403$ at $z = 3.832$ which is approximately determined with use of C II $\lambda 1036$ in the forest; in components 12 and 16 C II is mildly saturated, making the values listed for these less certain than the rest; there is weak associated C II* $\lambda 1336$: for components 4, 12 and 16 C II*/C II averages $(3.4 \pm 1.1) \times 10^{-3}$. The Si II values are from $\lambda 1527$: component 1 has strong contamination by atmospheric line emission and values in components 10, 18 and 19, which have only upper limits, are too high to be useful.

^mC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 4.094$ but $\lambda 1548$ is clear.

ⁿC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 4.080$ but is strong and together with both C IV doublet members at $z = 4.080$ is well determined while $\lambda 1551$ is strongly contaminated by atmospheric line emission and not used. Si IV $\lambda 1403$ is blended with C IV $\lambda 1551$ at $z = 3.604$ but $\lambda 1394$ is clear although in a noisy region.

^oC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 4.086$ but $\lambda 1551$ is clear.

^pC IV $\lambda 1551$ in components 1 and 3 has strong contamination by atmospheric line emission but $\lambda 1548$ is clear. Si IV $\lambda 1394$ is weak and dominated by C IV $\lambda 1548$ at $z = 3.681$ but $\lambda 1403$ is clear. C II in components 1 and 2 is masked by C IV $\lambda 1548$ at $z = 3.482$ and Si IV $\lambda 1394$ at $z = 3.978$.

^qC IV $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 4.239$ but $\lambda 1548$ is clear. Si IV $\lambda 1394$ in components 1 and 2 contains some unidentified narrow features but $\lambda 1403$ is clear. C II in components 2–4 is in a very noisy region and in 5–7 is blended with Si IV $\lambda 1403$ at $z = 3.978$ but some useful upper limits are obtained.

^rC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 4.231$ while $\lambda 1551$ is blended with C IV $\lambda 1548$ at $z = 4.247$, but taking all associated doublets together good values are obtained. Si IV $\lambda 1403$ is blended with C IV $\lambda 1548$ at $z = 3.748$ but $\lambda 1394$ appears clear apart from a strong feature at observed wavelength $\lambda 5908.40$, at apparent redshift 4.239181 if $\lambda 1394$, where however no features are detected in C IV and C II, so this is probably an unidentified interloper and not entered in the table. C II is blended with Si II $\lambda 1304$ at $z = 4.361$ but this is very weak and only the value in component 3 is significantly affected.

^sC IV $\lambda 1548$ is blended with C IV $\lambda 1551$ at $z = 4.239$ while $\lambda 1551$ is strongly affected by atmospheric line absorption but together with the associated C IV doublets nearby in redshift good values are obtained. Si IV $\lambda 1403$ is partially blended with C IV $\lambda 1551$ at $z = 3.748$, while component 2 in $\lambda 1394$ has an interloper indicated by strong inconsistency with $\lambda 1403$ and is not used, but taken collectively the listed values are acceptable.

^tC IV $\lambda 1548$ contains very weak Si II $\lambda 1527$ at $z = 4.361$ and in component 3 includes strong atmospheric line absorption while $\lambda 1551$ in components 2 and 4 includes line emission, and both are in a rather noisy region, but together acceptable values are obtained.

^uC IV $\lambda 1548$ in components 2, 7 and 8 and $\lambda 1551$ in components 3 and 4 are contaminated by strong atmospheric line emission but together good values are obtained. Si IV $\lambda 1394$ in component 1 is blended with C IV $\lambda 1548$ at $z = 3.825$ and has mild interference by atmospheric line emission but $\lambda 1403$ is clear although in a rather noisy region. Si II is derived from a combination of complementary portions of $\lambda 1260$ (in the forest but useful) and $\lambda 1304$ (partially blended with C II $\lambda 1335$ at $z = 4.239$), while $\lambda 1527$ is partially blended with C IV $\lambda 1548$ at $z = 4.286$ and rather noisy and is not used; errors and upper limits are from $\lambda \lambda 1260, 1304$.

^vC IV values are dominantly from $\lambda 1551$ as $\lambda 1548$ is heavily contaminated by atmospheric line emission and has other apparent interference. Si IV $\lambda 1394$ is masked by strong Al III $\lambda 1863$ at $z = 3.032$ but $\lambda 1403$ is clear except for component 1 which is obscured by atmospheric line emission. Si II $\lambda 1260$ is outside the forest.

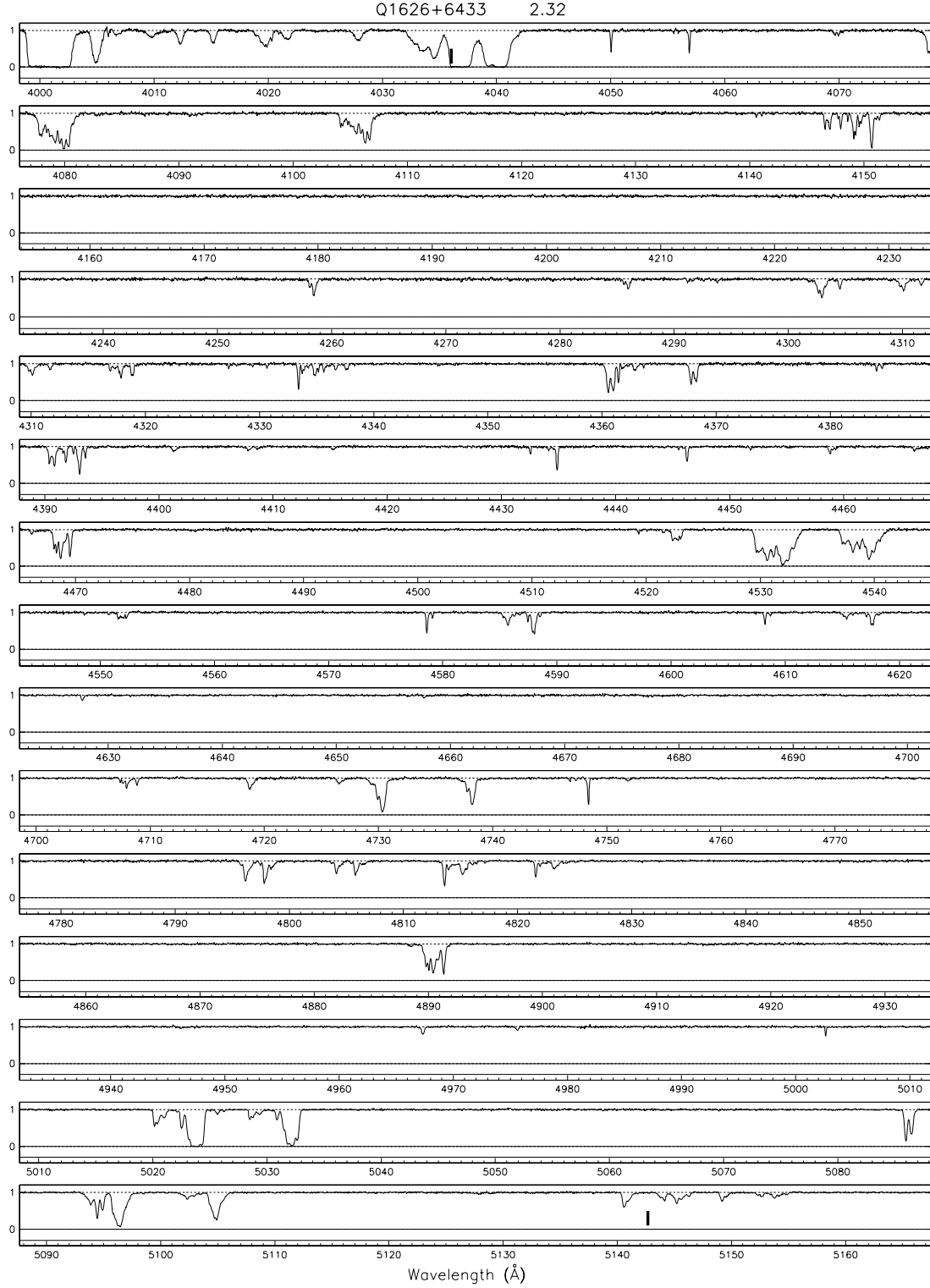


Fig. 1.— Continuum-normalized spectra of the nine QSOs in observed wavelengths reduced to heliocentric vacuum values, scaled to cover the same rest wavelength range: *thick vertical ticks* place the QSO broad Lyman α and C IV lines. Atmospheric line features are indicated by *graded thin vertical ticks* (emission) and *inset spectra below* (absorption); both reflect the heliocentric corrections over the runs (see text and Tables): the QSO spectra are “cleaned” of resultant interference for display.

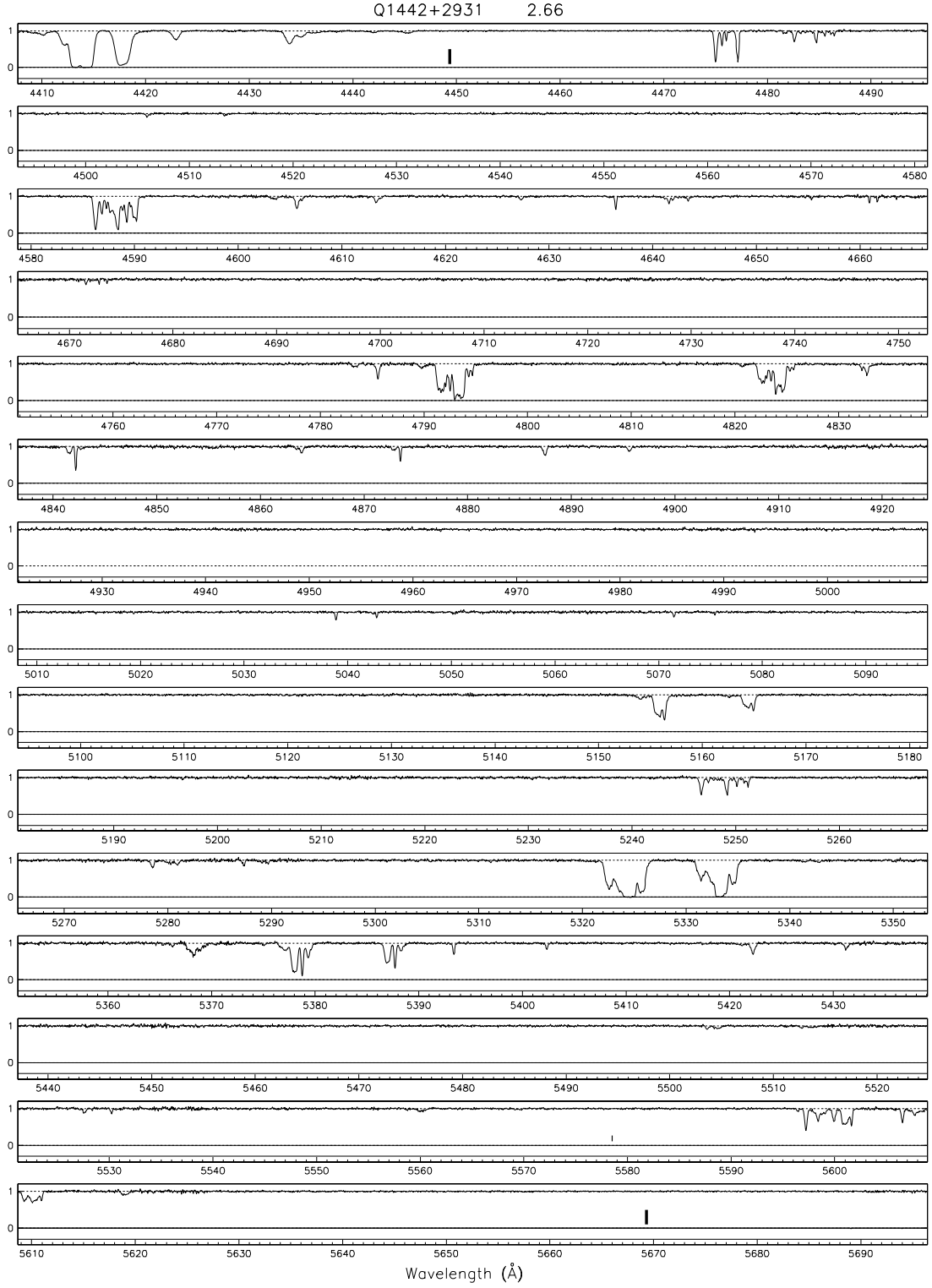


Fig. 1.— Continued.

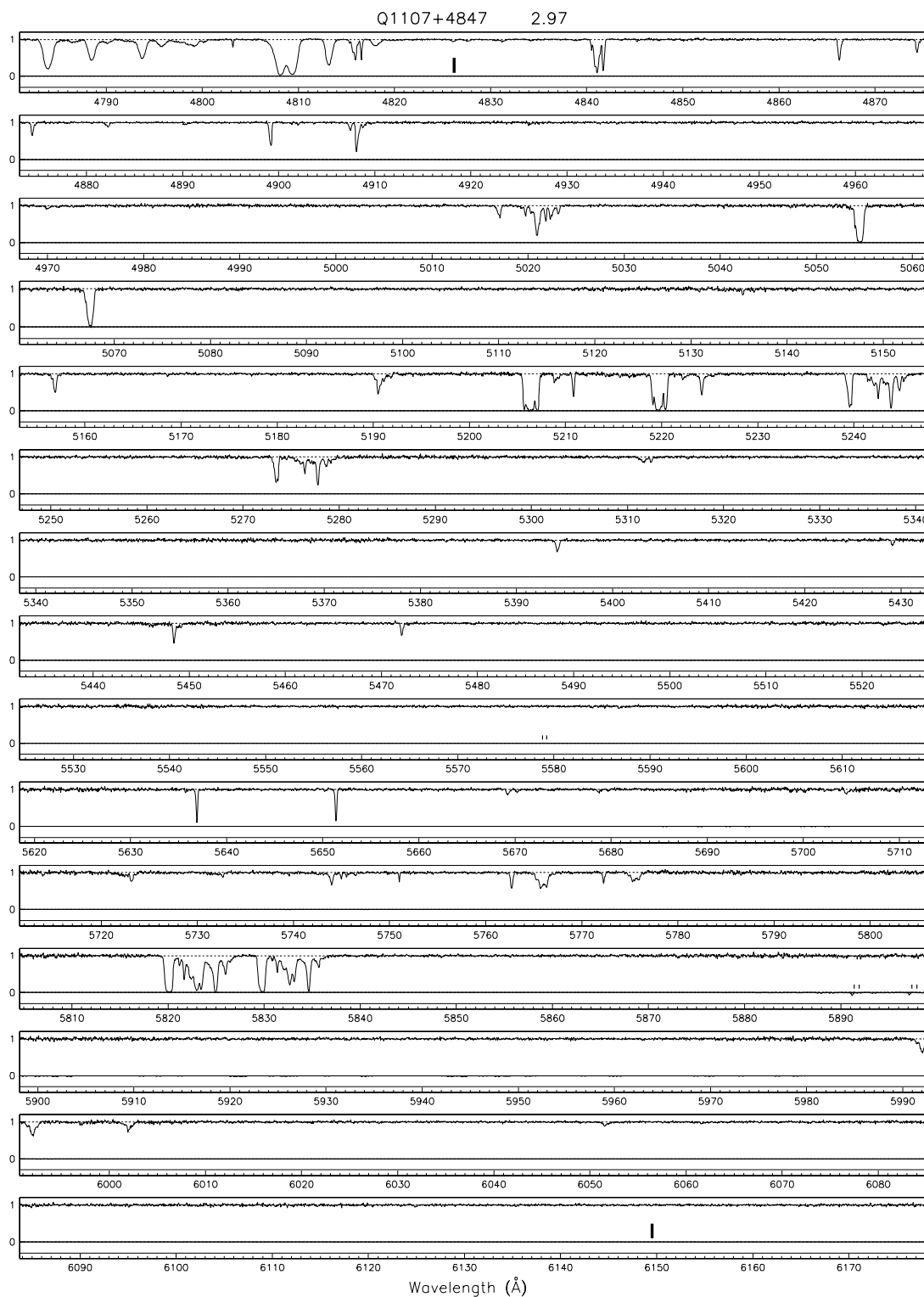


Fig. 1.— Continued.

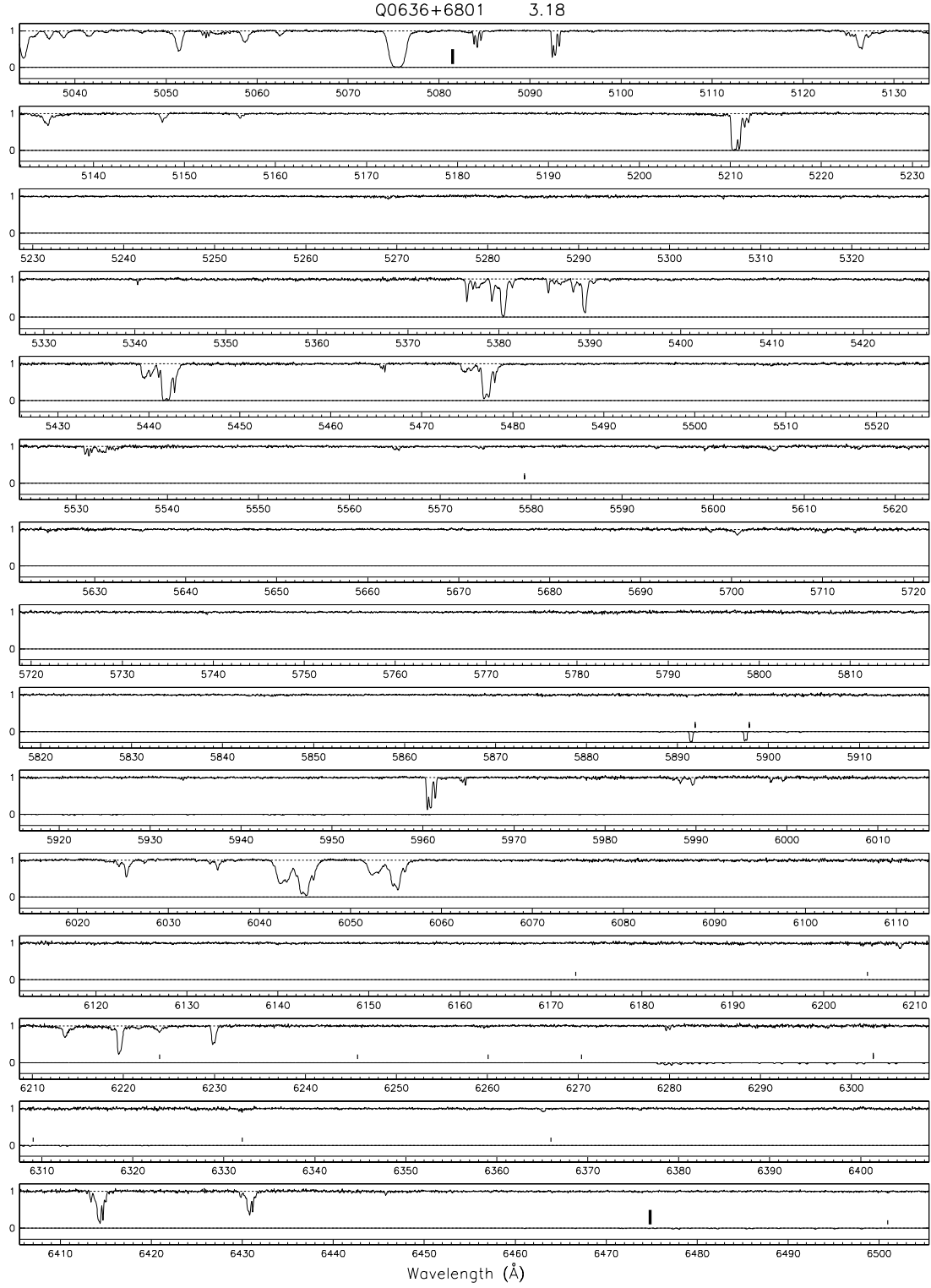


Fig. 1.— Continued.

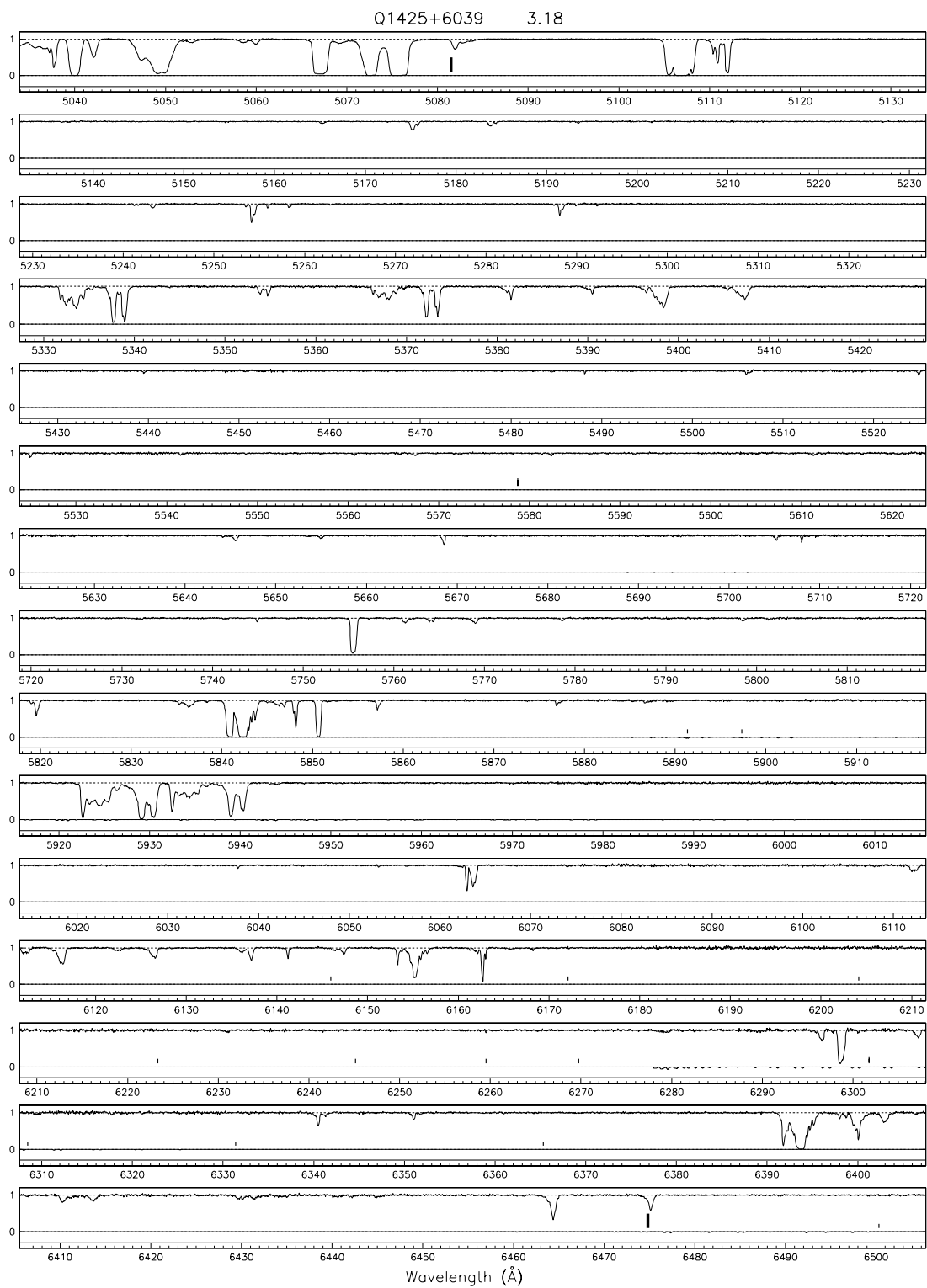


Fig. 1.— Continued.

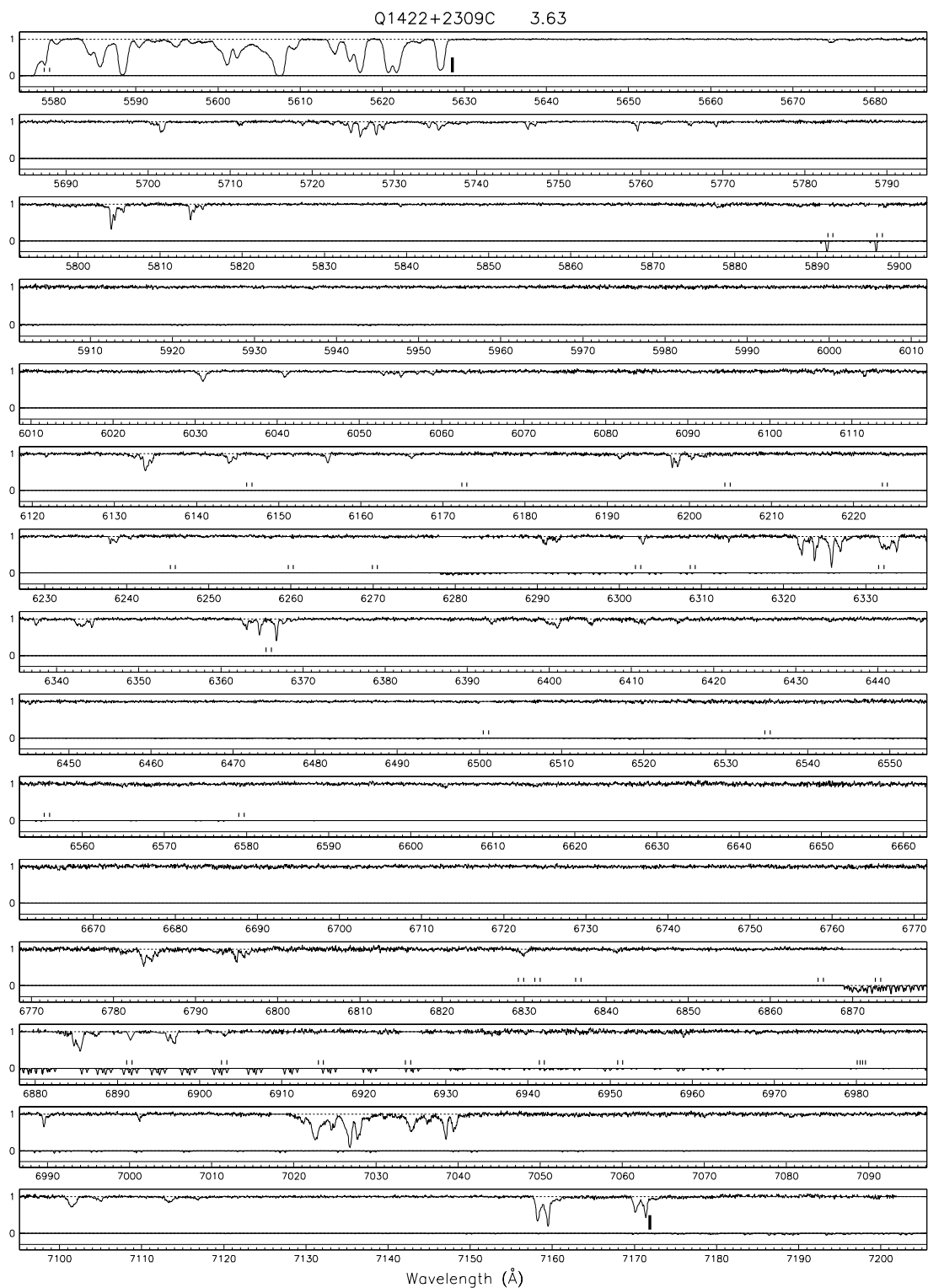


Fig. 1.— Continued.

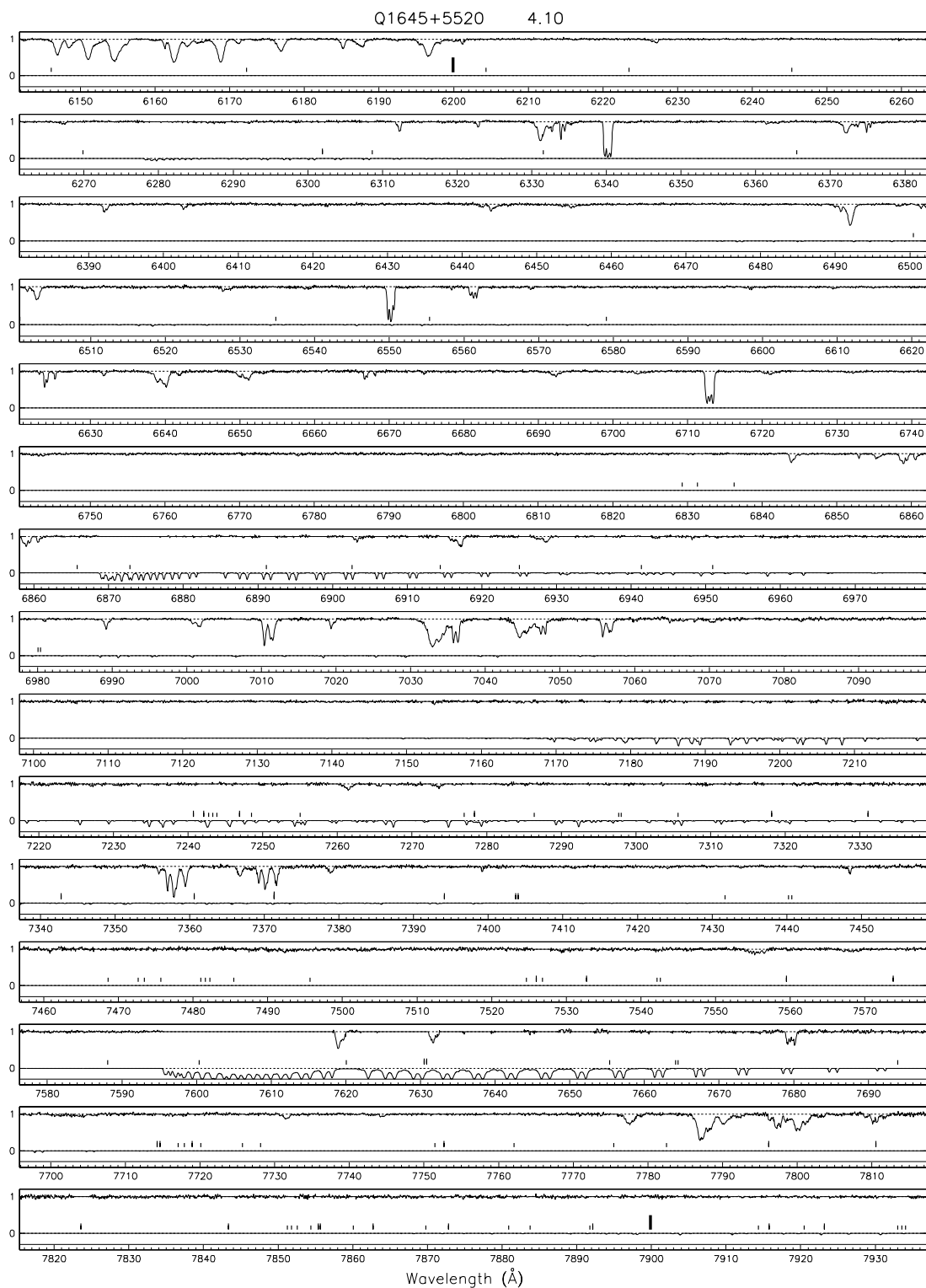


Fig. 1.— Continued.

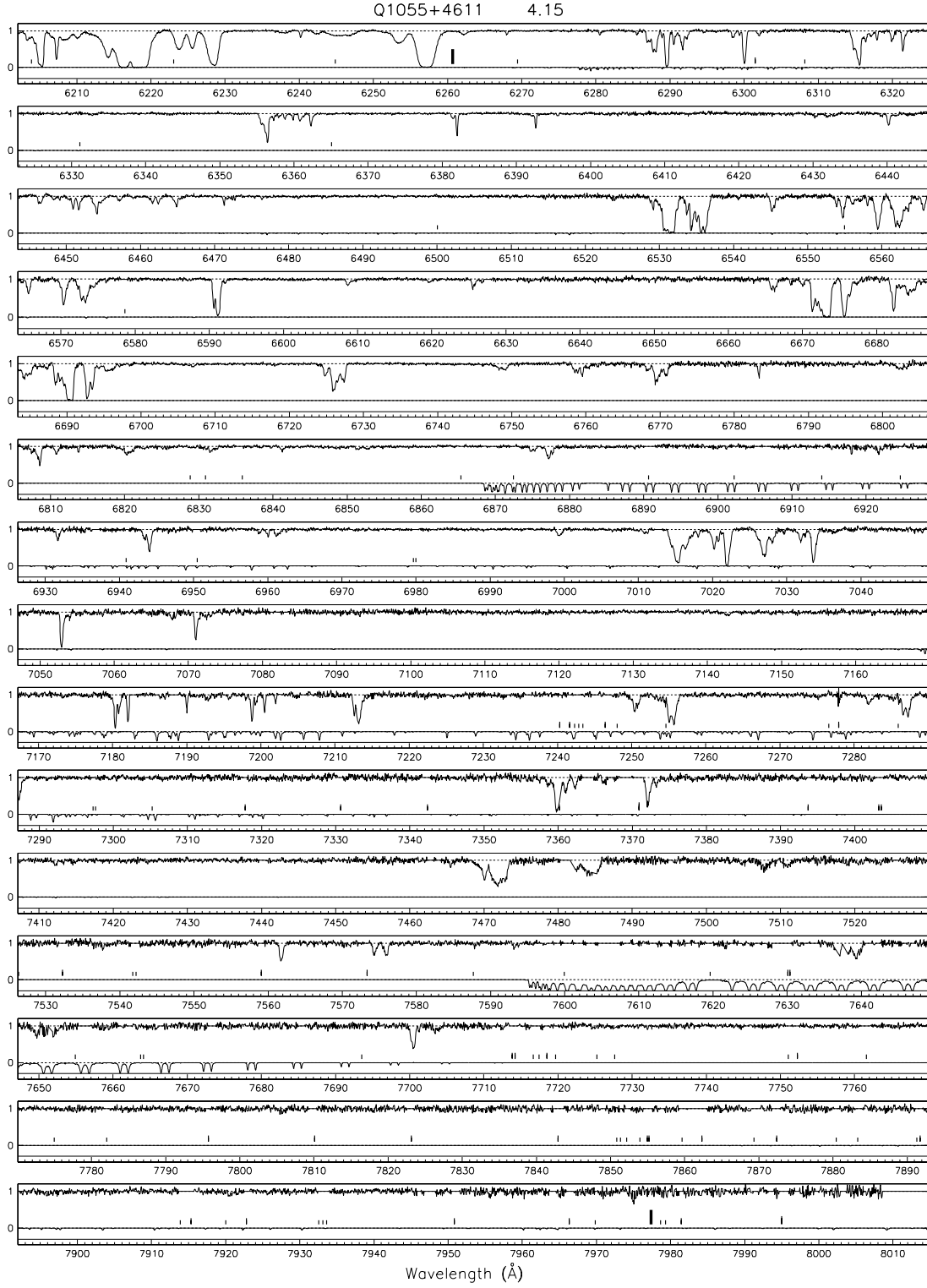


Fig. 1.— Continued.

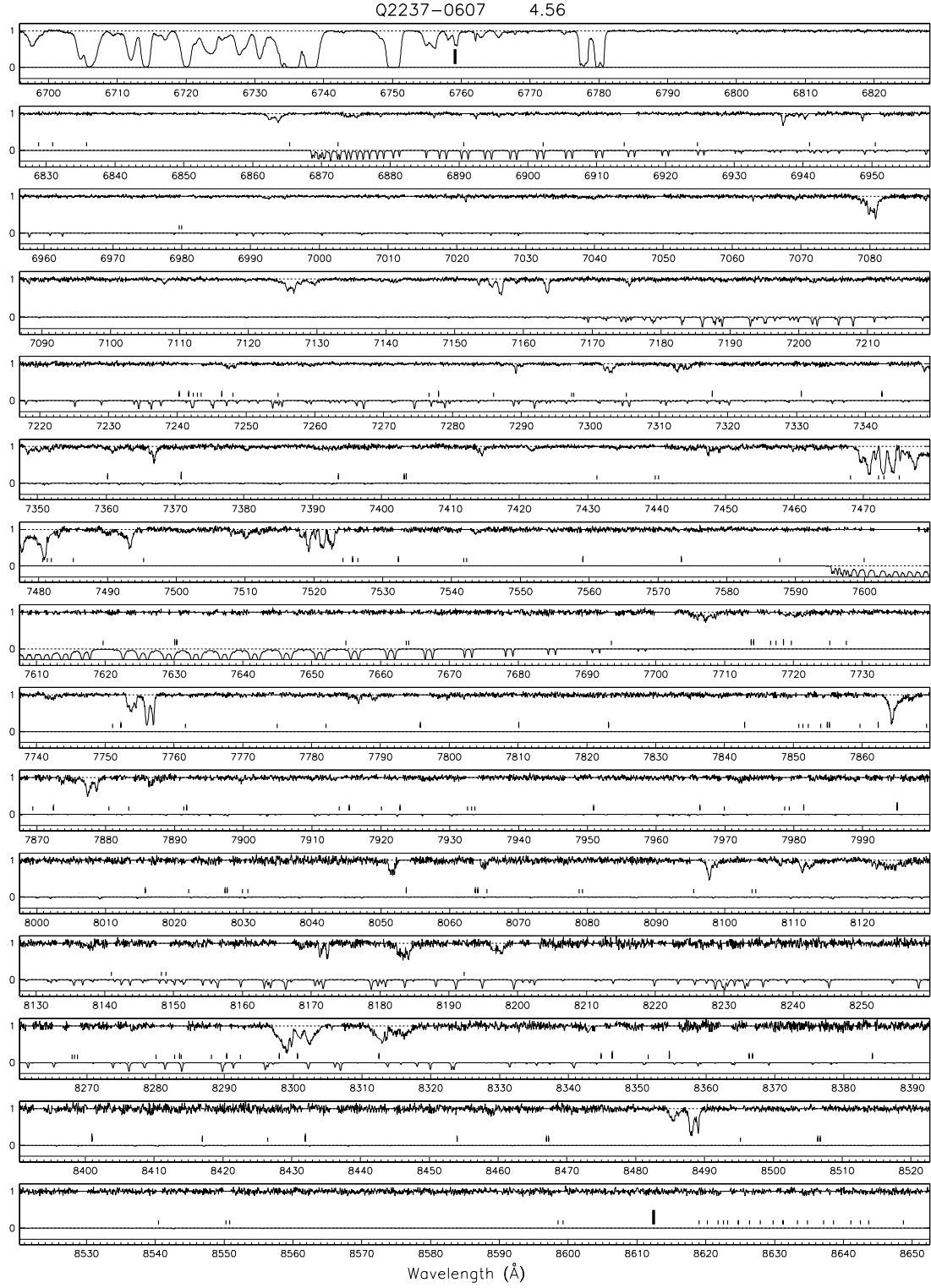


Fig. 1.— Continued.

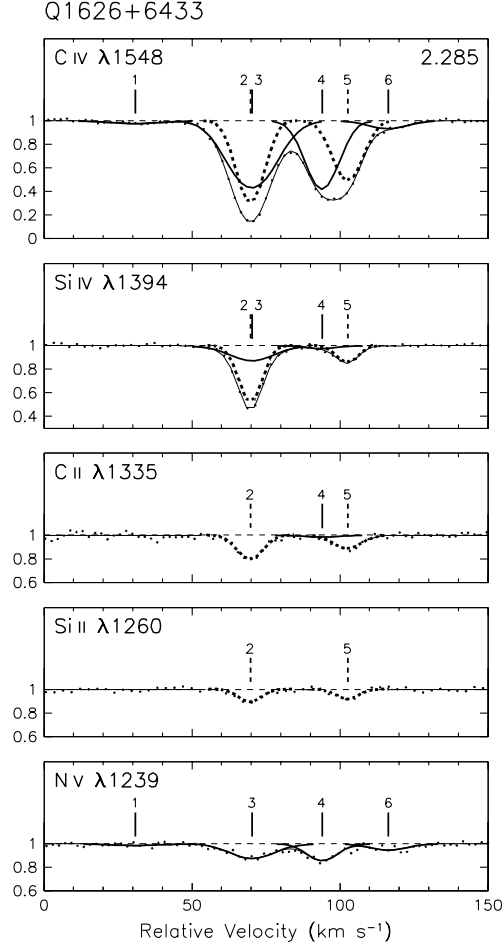


Fig. 2.— C IV $\lambda 1548$, Si IV $\lambda 1394$, C II $\lambda 1335$, Si II $\lambda 1260$ and N V $\lambda 1239$ continuum-normalized spectra for the $z = 2.285$ absorption system in Q1626+6433, demonstrating the separation into *single-phase-ionization components* by means of the VPFIT analysis (see §3.2 in the text for a full description). The complete data set for this system (including all observed transitions) is shown in Figure 4. For each profile the composite fit through the system data points is shown by a *thin continuous line* where not covered by individual component fits. Parameters of the constituent components indicated by the *numbered vertical ticks* are given in Table 2. Ticks are shown only at the positions of *detected* components, not upper limits. The six components shown separated with individual fits in the C IV profile are reflected in partial fashion among the Si IV, C II, Si II and N V profiles, with the components that are dominant in C II (low ionization) identified by *dashed lines and ticks* and those dominant in N V (high ionization) by *thick continuous lines and ticks*. Note the two nearly coincident (in redshift) components 2 and 3 having markedly different widths: both are strong in C IV but differ greatly among the other species (see text). Component 4 which is strong in both C IV and N V still is weakly evident in the Si IV and C II profiles.

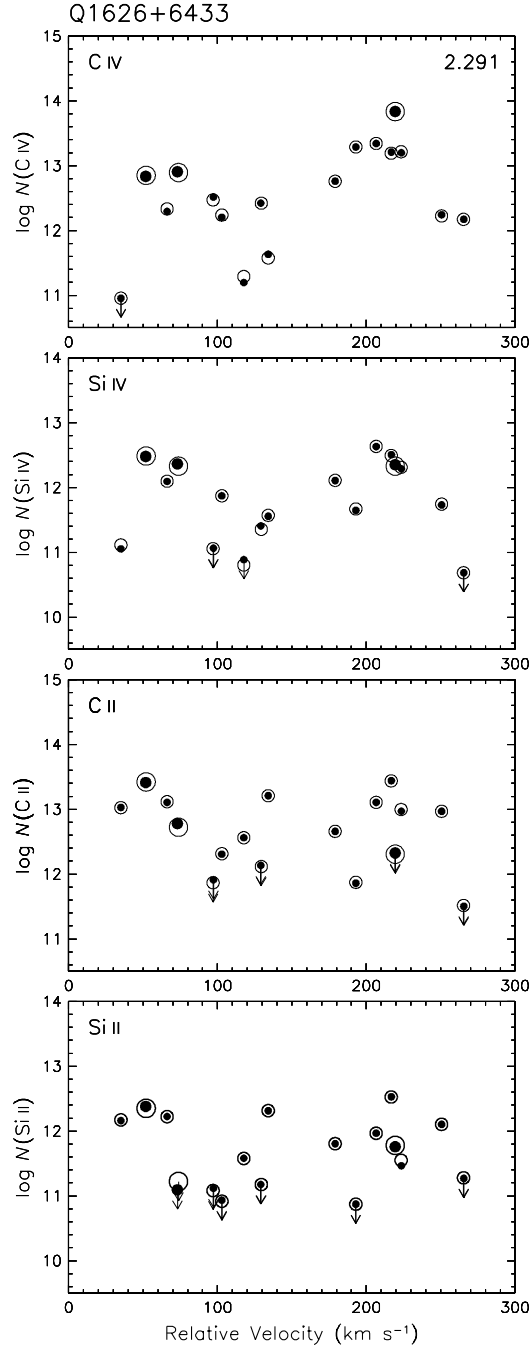


Fig. 3.— C IV, Si IV, C II and Si II component column densities N (cm⁻²) for the complex absorption system at $z = 2.291$ in Q1626+6433 (see Figures 4 and 6 and Table 2 for identification). Two individual runs in the VPFIT analysis show the differential effect of fixing the set of three broadest components (indicated by *enlarged symbols*) at the two widely separated temperatures 1×10^4 K and 1×10^5 K, but otherwise having the same mix of specific starting values for the remainder of the components (see text). All component values yielded in the first case are shown by *filled circles* and in the second by *open circles*.

Q1626+6433

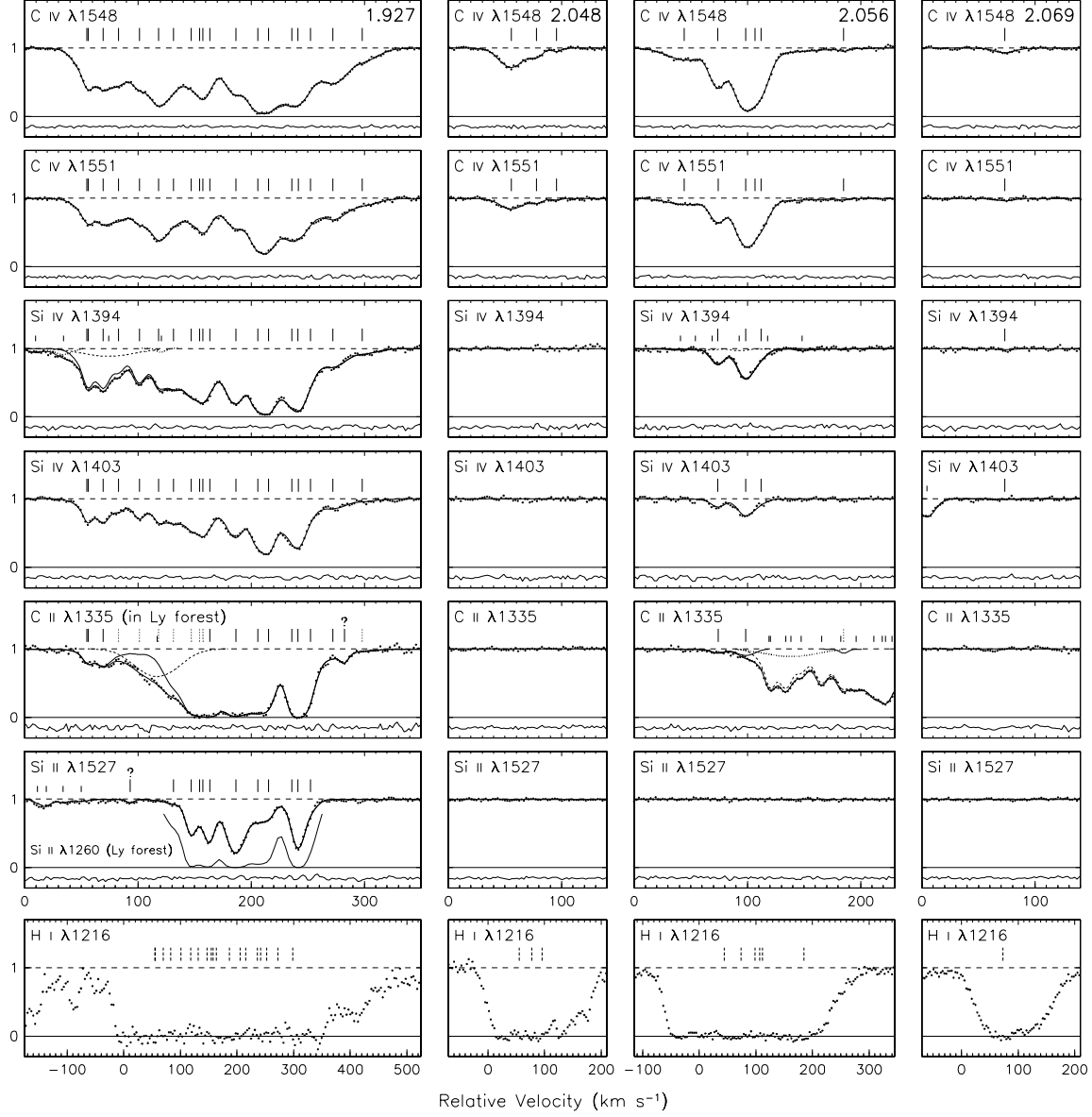


Fig. 4.— Continuum-normalized spectra for all systems detected in Q1626+6433 ($z_{em} = 2.32$) having at least C IV and Si IV outside the Lyman forest, as an example of the outcome of the line-fitting procedure. For each system the available metal species of interest in this paper are compared on a common velocity scale. The system components identified using VPFIT are marked with *long vertical ticks*; a few questionable features are so indicated. Components yielding only upper limits are unmarked. Component parameter values and upper limits are listed in Table 2; in the few cases where components have values which are too uncertain to be included in the table, as indicated in associated notes, they are marked with *dotted ticks*. Blended or nearby interloper species from other systems, also indicated in the notes, are marked with *short ticks*. The observed data values are given as points and the overall fits obtained to these are shown as *continuous lines*; overall residuals (i.e., [data] – [fit]) are shown on the same scale beneath the profiles. When blending is present the deconvolved fits to the species under consideration again are shown as *continuous lines* and fits to individual interloper species by *short-dashed or dotted lines*. Si II $\lambda 1527$ at $z = 1.927$ and $z = 2.110$ have superimposed fits to $\lambda 1260$ (in these cases found in relatively clear regions of the forest and matching the data well) shown as *continuous thin lines*. Lyman α observations, covering twice the velocity range, are shown unfitted, but with the positions of all components detected in C IV indicated by *broken ticks*.

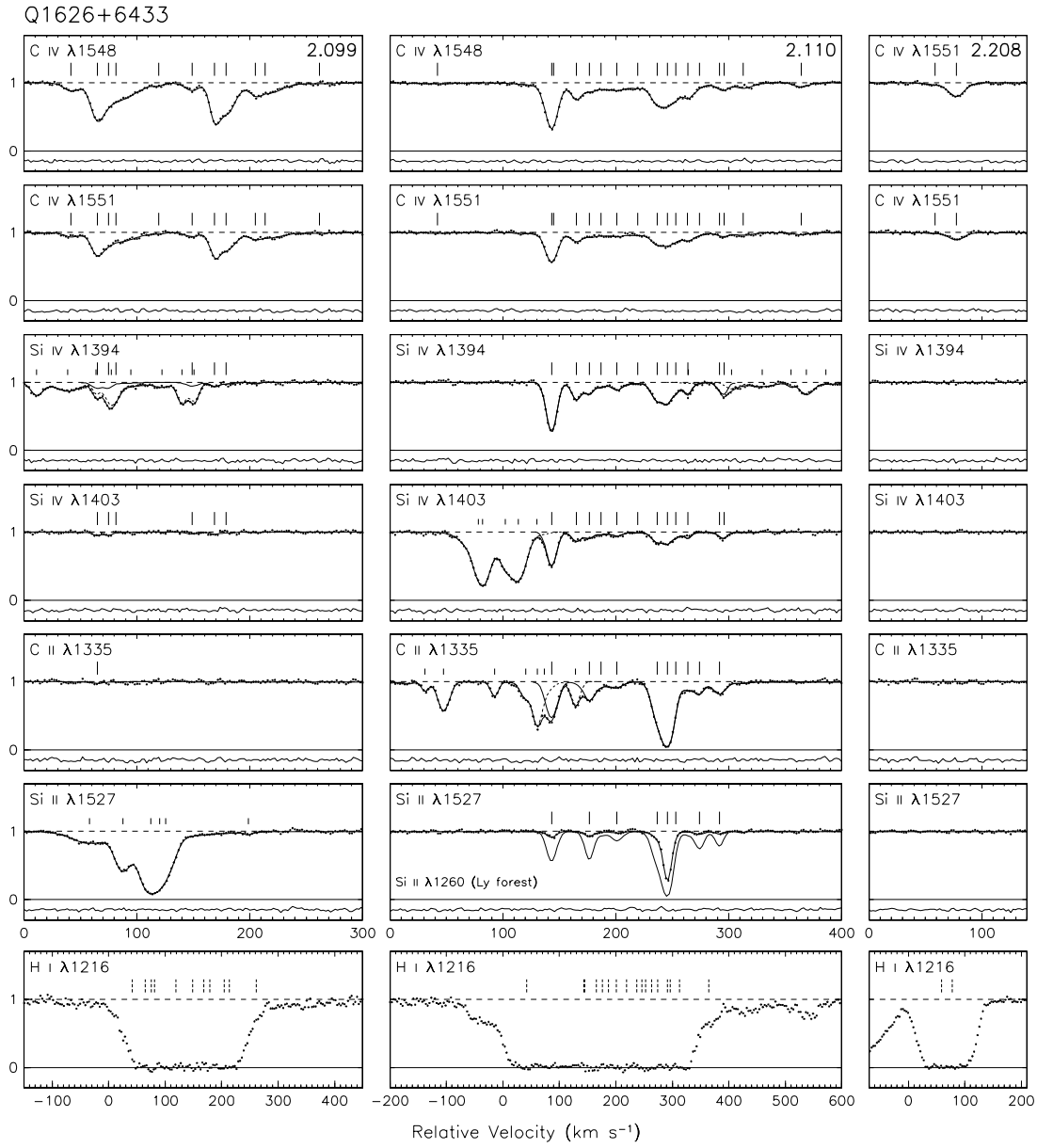


Fig. 4.— Continued.

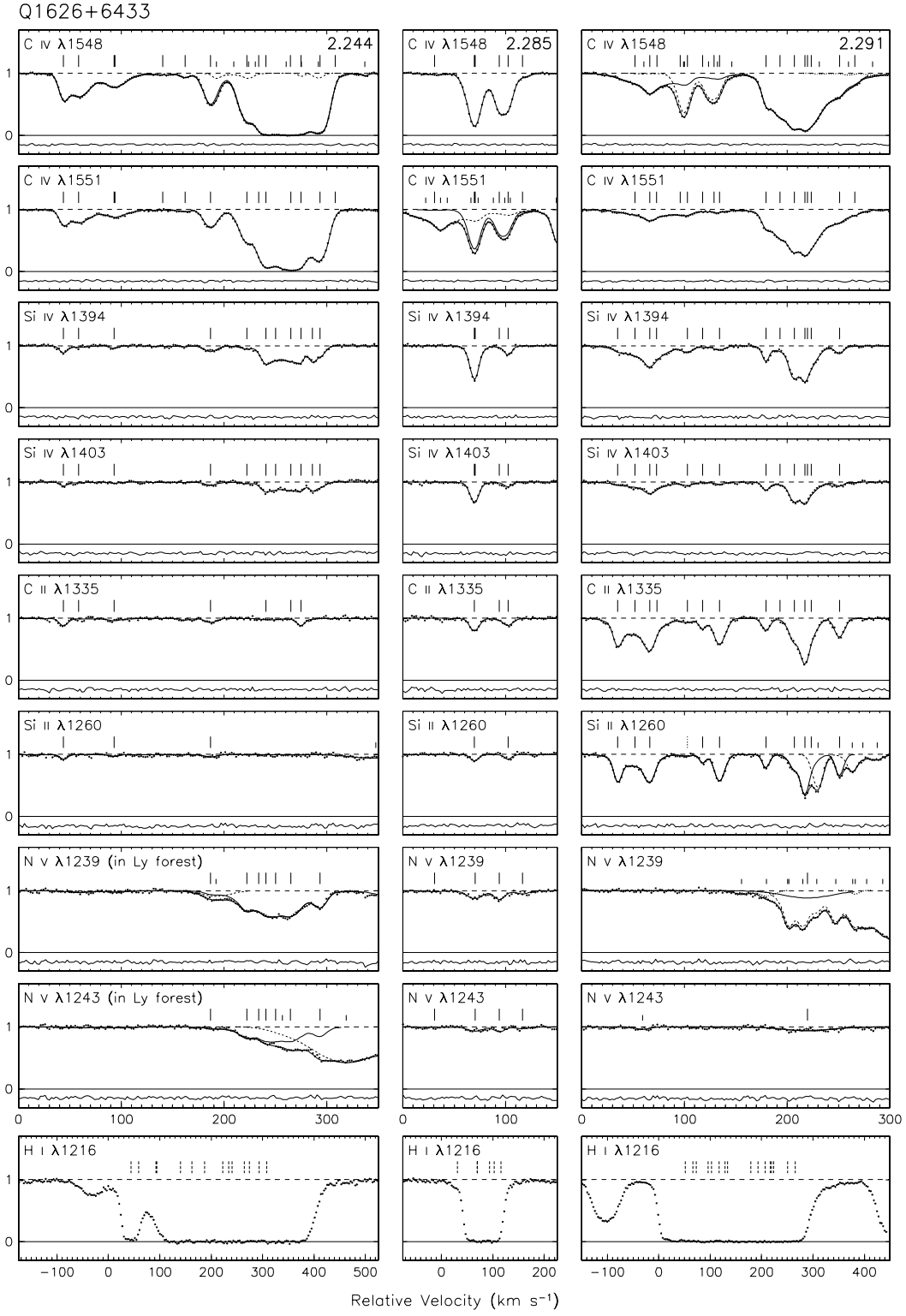


Fig. 4.— Continued.

Q1626+6433

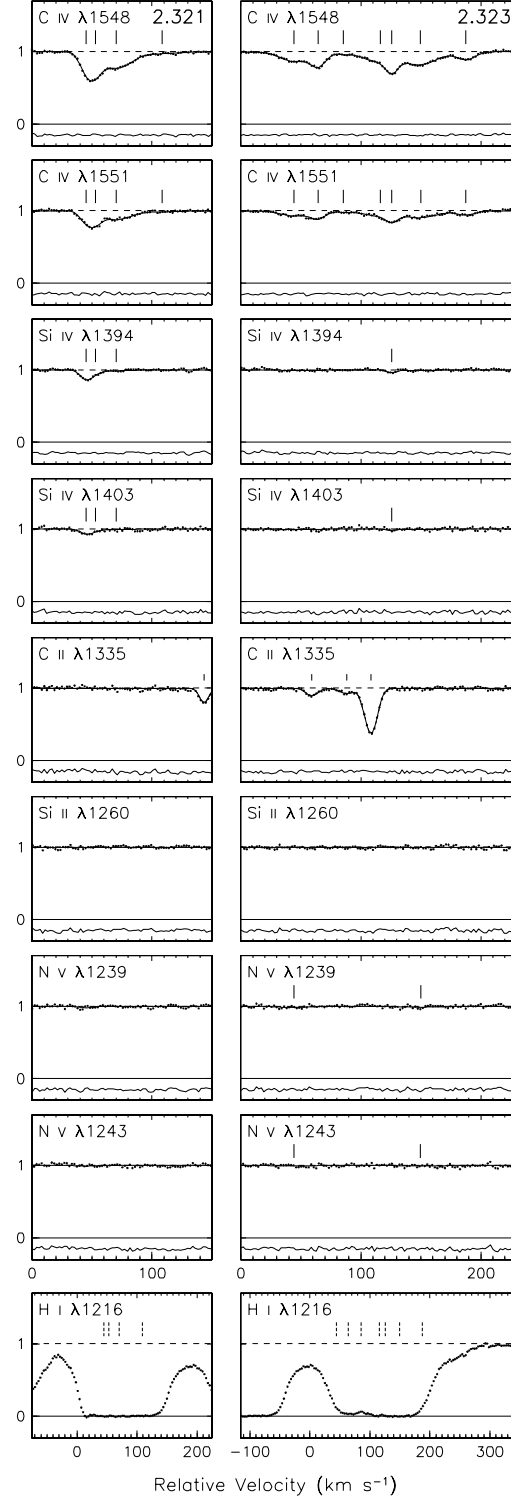


Fig. 4.— Continued.

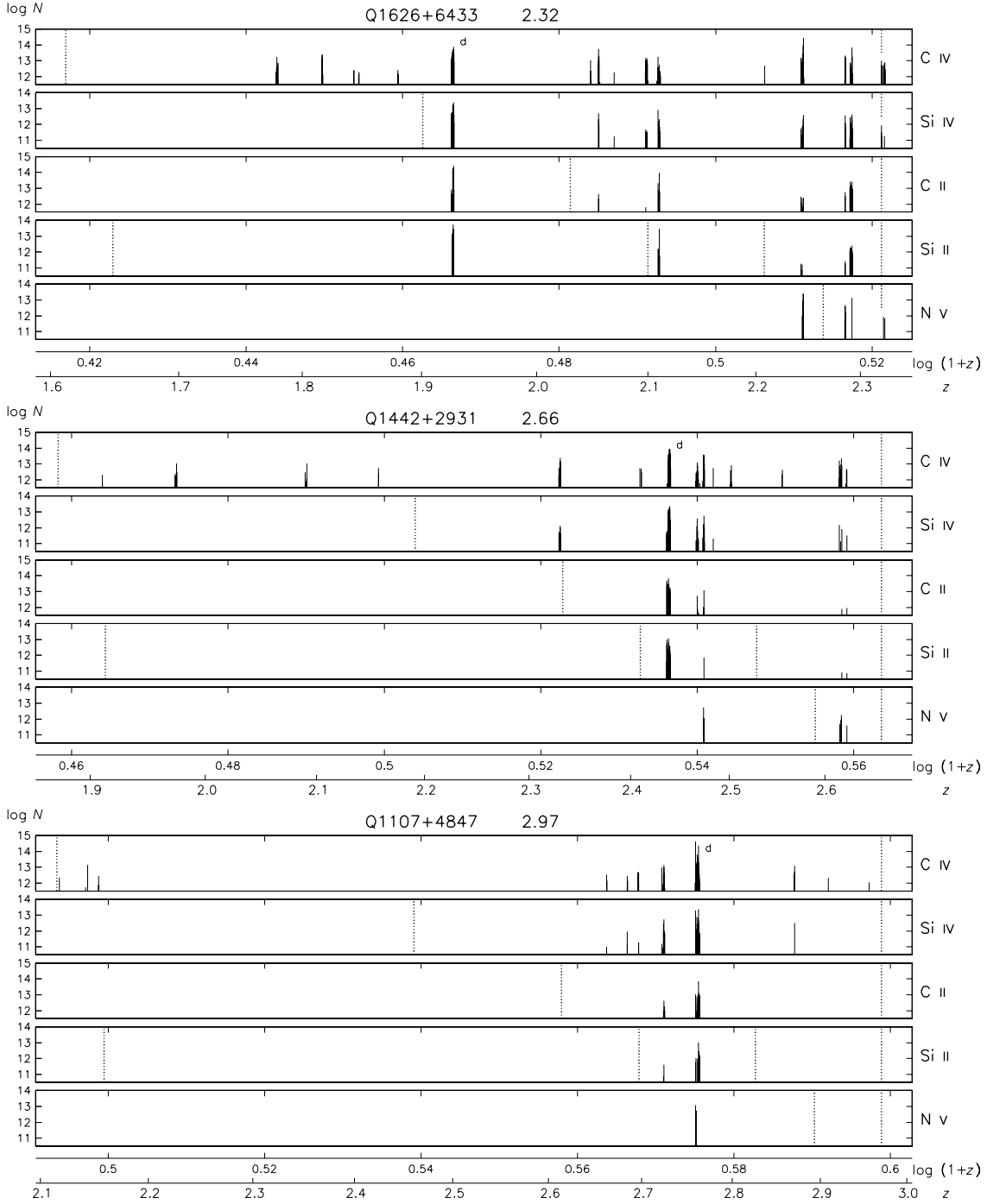


Fig. 5.— C IV, Si IV, C II, Si II and N V column densities N (cm^{-2}) plotted against redshift z and $\log(1+z)$ for the absorber components *detected* in the nine QSOs, including the few bracketted values (see Tables 2–10). Errors and upper limits are not shown. Systems containing one or more components with significant Lyman α damping wings are marked d. Note, the vertical scales for Si IV, Si II and N V are shifted lower by 1 dex than the other two. All frames cover the same extent in $\log(1+z)$, which for C IV encompasses the region between the QSO Lyman α and C IV emission lines with some margin. The *dotted vertical line* at the right of each frame is at the emission redshift indicated in the heading; the similar line to the left of this marks the limit where a given ion falls in the Lyman forest (for Si II the limits for $\lambda 1260$, $\lambda 1304$ and $\lambda 1527$ are included; the *strong* components appearing to the left of the $\lambda 1260$ and $\lambda 1304$ boundaries are invariably $\lambda 1527$). Reliable values for Si IV, C II, Si II and N V appear at redshifts in the forest where clear (such cases are few), as clarified in the table footnotes.

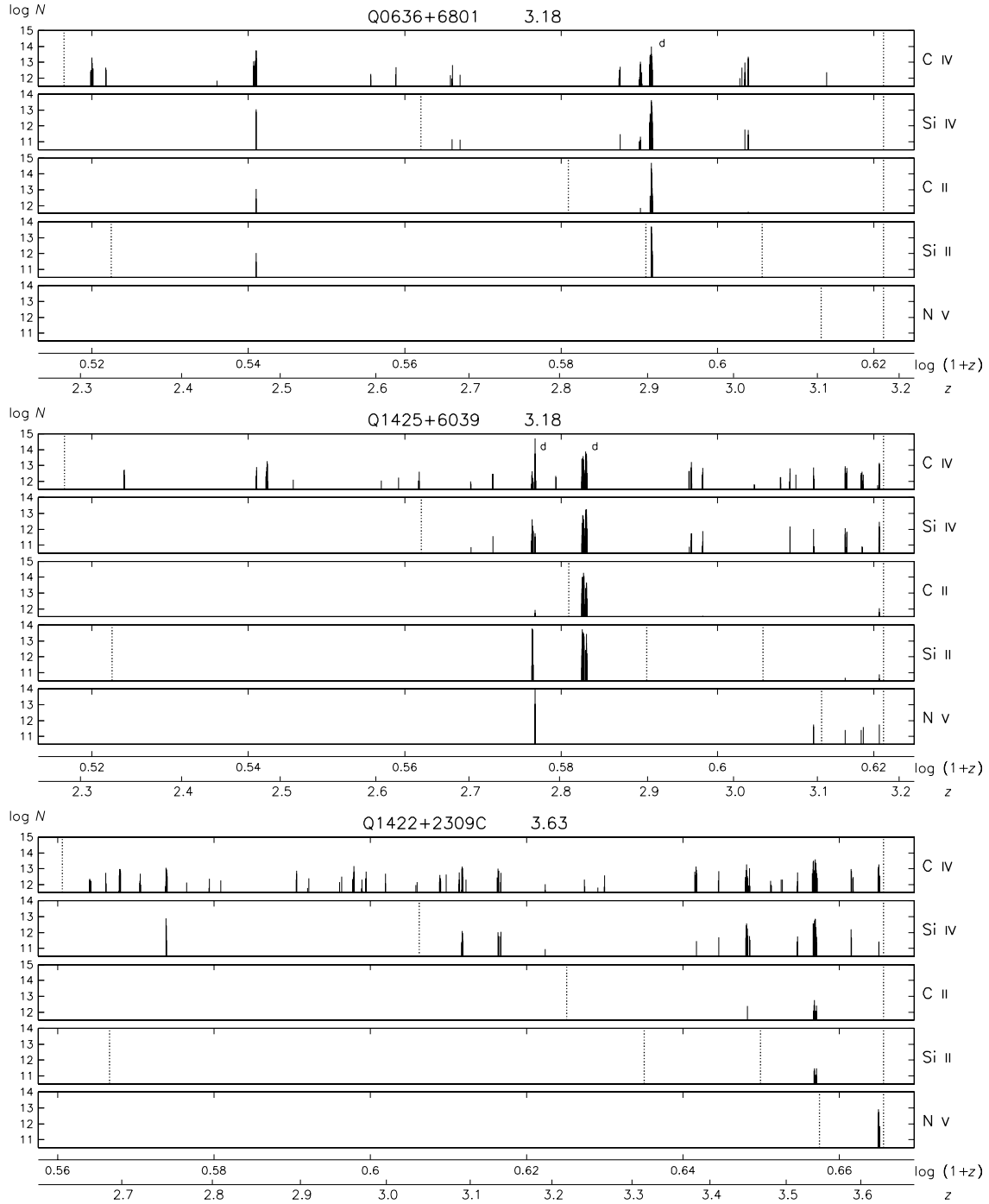


Fig. 5.— Continued.

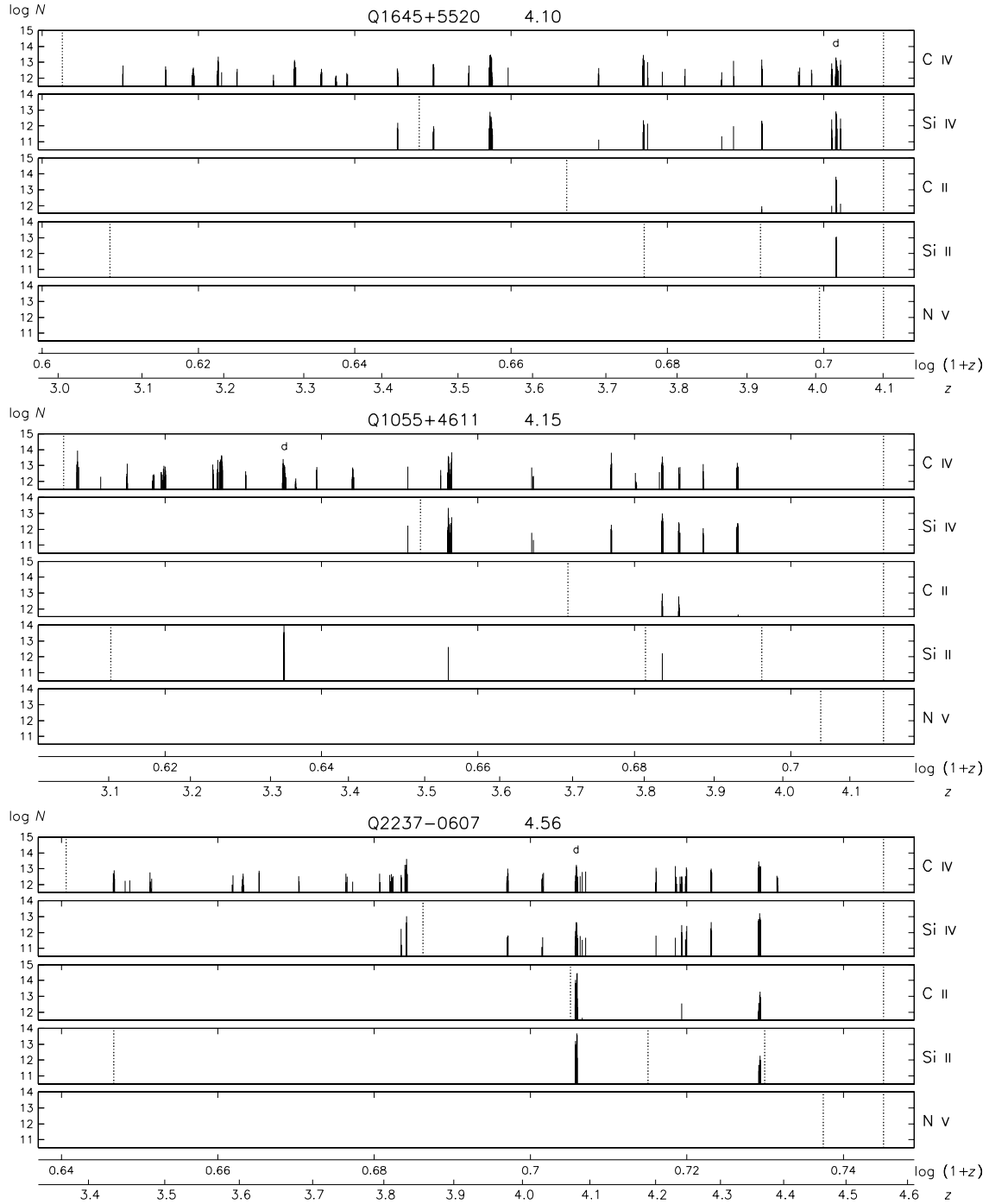


Fig. 5.— Continued.

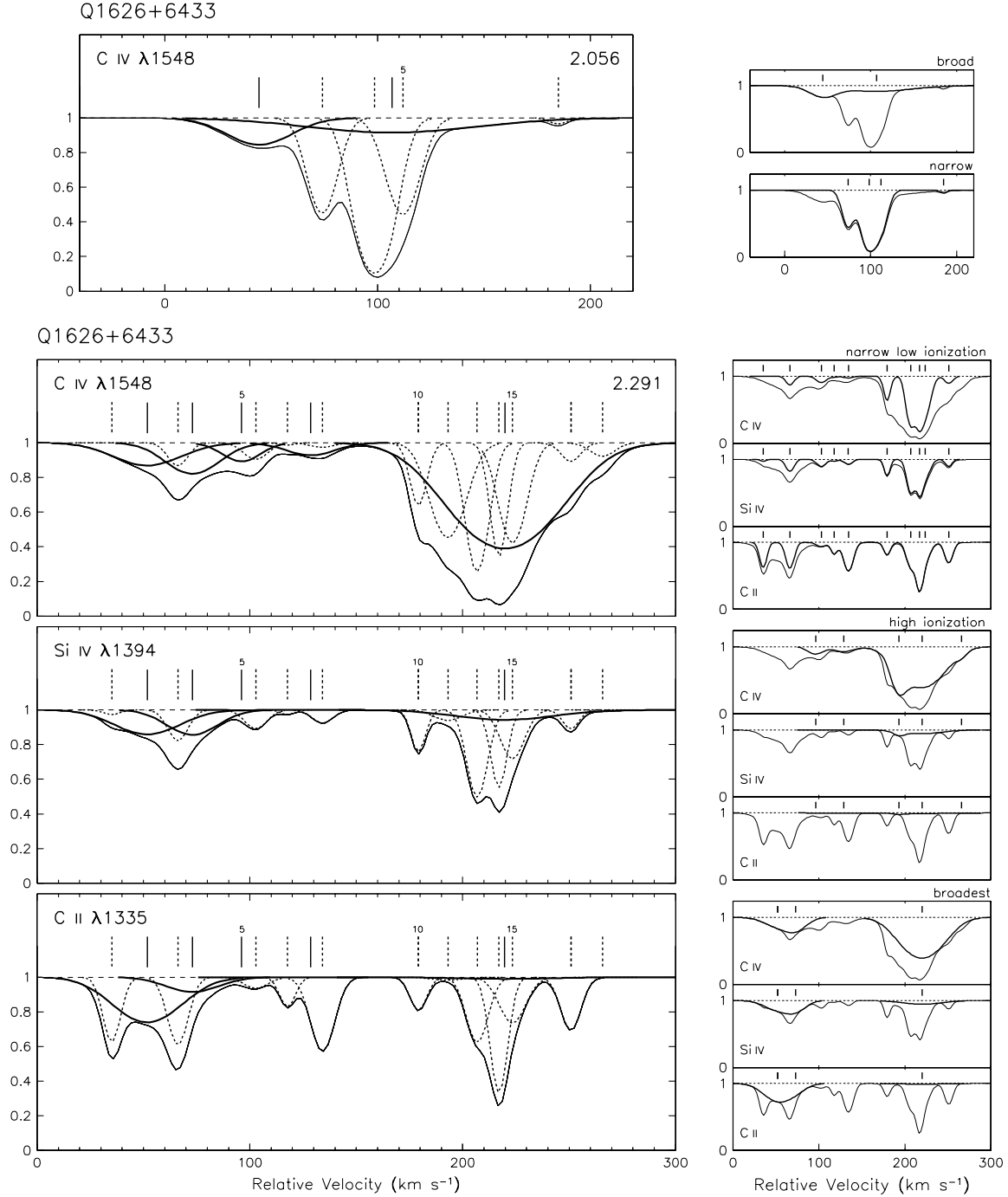


Fig. 6.— Two examples from Q1626+6433 displayed in Figure 4, showing details of the derived VPFIT components of systems containing *broad* components (*continuous thick lines and ticks*) among the more numerous *narrow* components, $b(\text{C IV}) \lesssim 10 \text{ km s}^{-1}$ (*dashed lines and ticks*), with numbering as in Table 2. Unlike in Figure 4 the ticks here *include* positions of upper limits. The overall composite fits to the pure system profiles (*i.e.*, excluding any interloper species) are shown in *continuous thin lines*. *Upper panels: left*, C IV profile in a simple system with exposed broad components; *right*, separately highlighting the composite profiles of the *broad* and *narrow* components. *Lower panels: left*, C IV, Si IV and C II profiles in a complex system with immersed broad components; *right*, separately highlighting the composite profiles of *narrow components* which are strong in C II, *all high ionization components* and the *broadest* components.

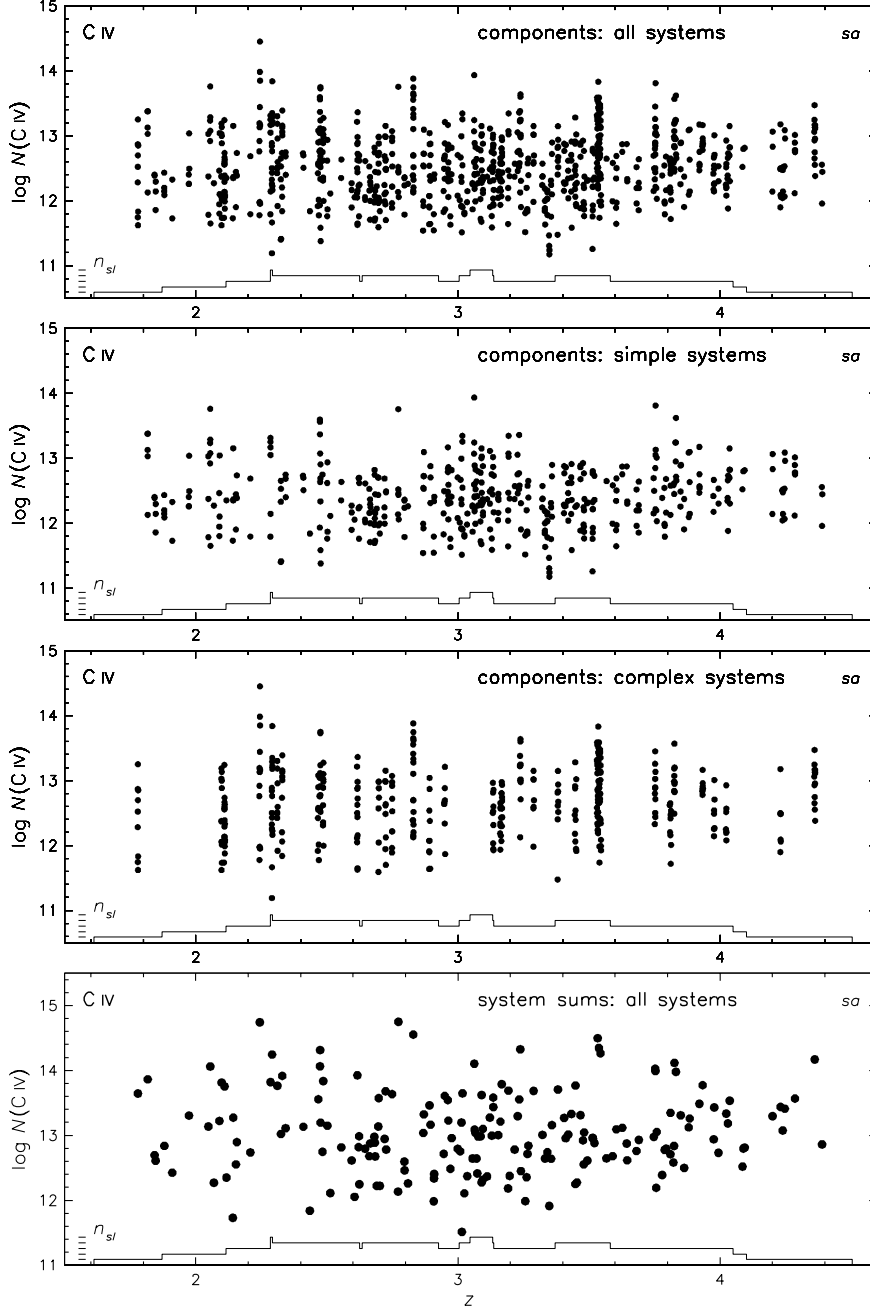


Fig. 7(a).— Detected C IV component and system column densities N (cm^{-2}) in sample *sa* for systems with velocity $\gtrsim 3000 \text{ km s}^{-1}$ from the nominal redshift z_{em} of their sightline QSO, plotted against redshift z . To avoid clutter, errors (see Tables 2–10) are not shown. The *thin continuous histograms* display (in unit steps) the redshift distribution of the number of contributing sightlines (n_{sl}) from the nine QSOs of the sample within the applied redshift constraints. *Upper three panels: component* values in *all* systems, *simple* systems (≤ 6 identified components) and *complex* systems (≥ 7 identified components). The vertical distributions manifest membership of systems. *Bottom panel: summed* column densities of the components within *all* systems.

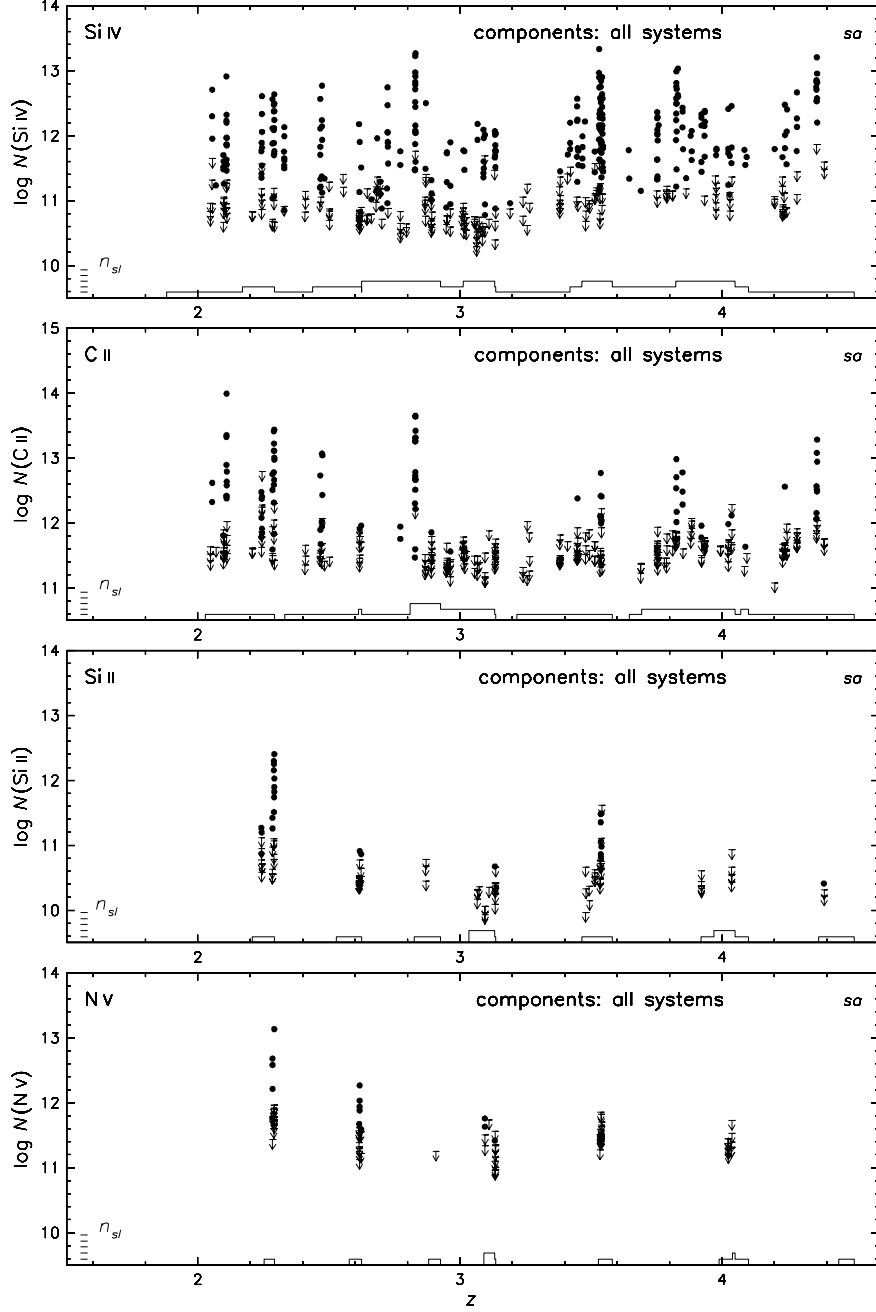


Fig. 7(b).— Si IV, C II, Si II and N V *component* column densities N (cm^{-2}) for all C IV detections in sample *sa*, following the style of Figure 7(a) but here for *all* systems only; upper limits related to these are 1σ values.

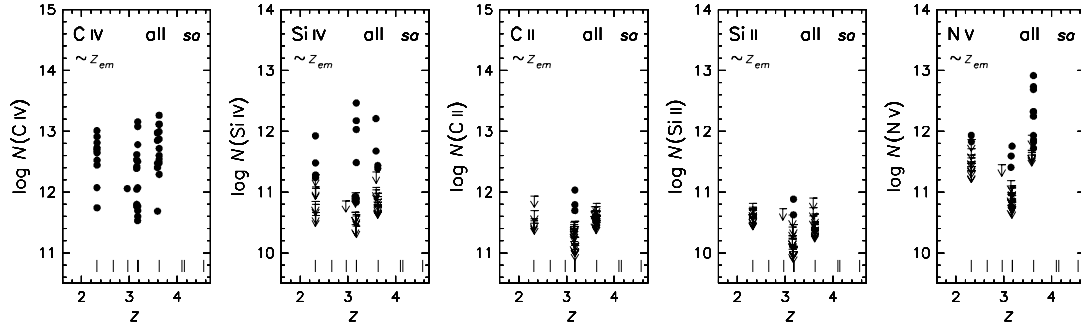


Fig. 8.— C IV, Si IV, C II, Si II and N V *component* column densities N (cm^{-2}) in sample *sa* for systems with velocity $\lesssim 3000 \text{ km s}^{-1}$ from the nominal redshift z_{em} of their sightline QSO (z_{em} for all nine QSOs are indicated by *vertical ticks*).

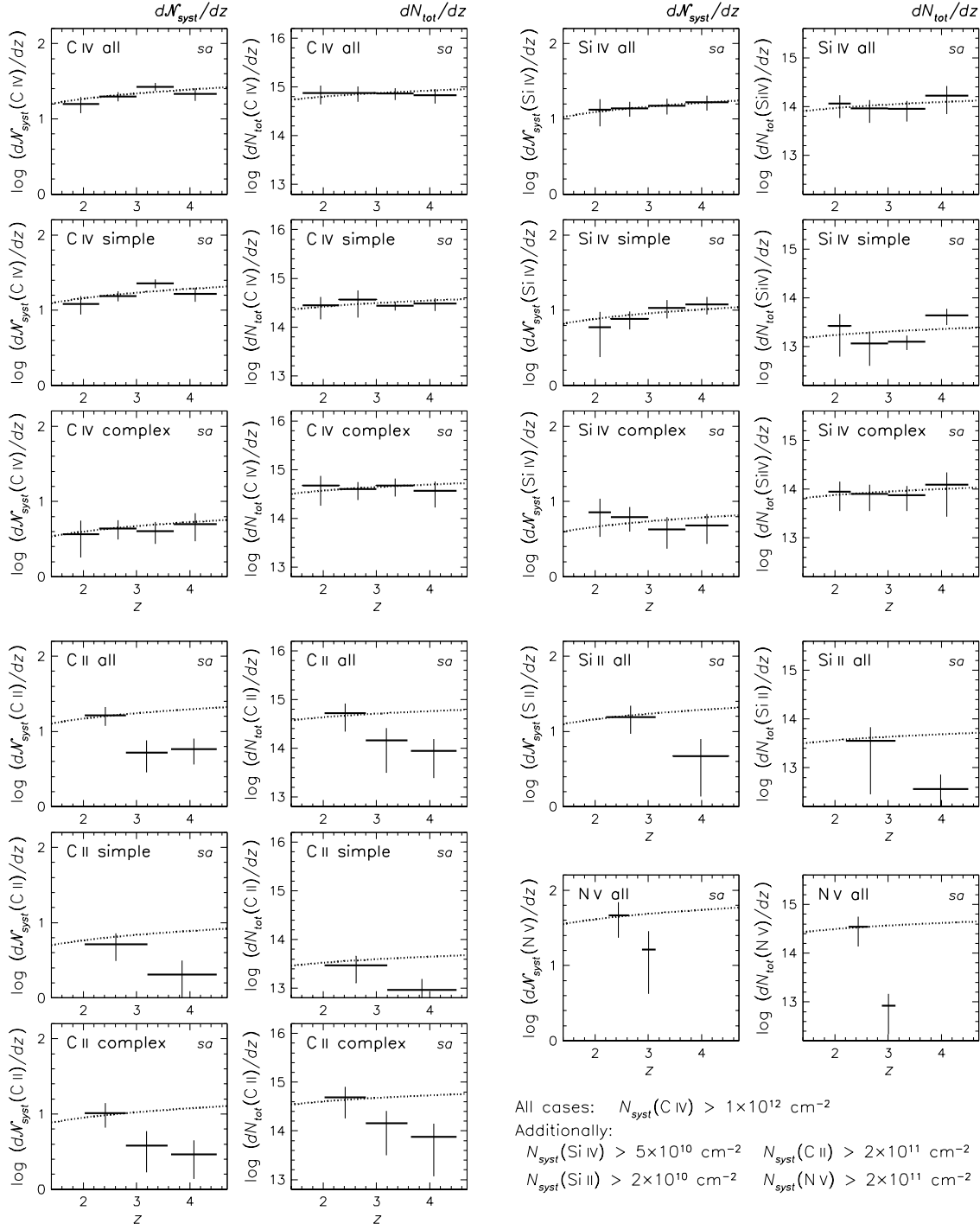


Fig. 9(a).— *Upper left panels:* Redshift evolution of C IV total number of *systems* per unit redshift interval, dN_{syst}/dz , and total column density (cm^{-2}) per unit redshift interval, dN_{tot}/dz , accounted over the redshift range shown by each bar and including correction for multiple sightlines (indicated in Fig (a) and (b)), for systems in sample *sa* having $N_{\text{syst}}(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$, showing *all* systems, *simple* systems (≤ 6 C IV components) and *complex* systems (≥ 7 C IV components); for errors see text. *Upper right and lower left panels:* Corresponding data for the same systems also having *detected* components in Si IV and C II above the indicated thresholds. *Lower right panels:* Similarly for *all* systems having *detected* components in Si II and N V. Note the various changes in vertical scale for dN_{tot}/dz . The dotted curves indicate non-evolving quantities (see text) vertically scaled for ready comparison with the data.

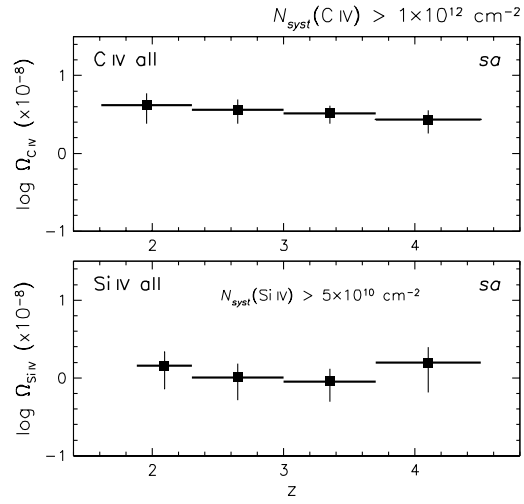


Fig. 9(b).— Redshift evolution of C IV and Si IV cosmological mass densities for *all* systems in sample *sa* having $N_{syst}(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$ and in the *lower* panel *additionally* $N_{syst}(\text{Si IV}) > 5 \times 10^{10} \text{ cm}^{-2}$, from the corresponding data for dN_{tot}/dz shown in the uppermost panels of Figure 9(a) and here similarly accounted over the redshift ranges indicated by the horizontal bars (see text).

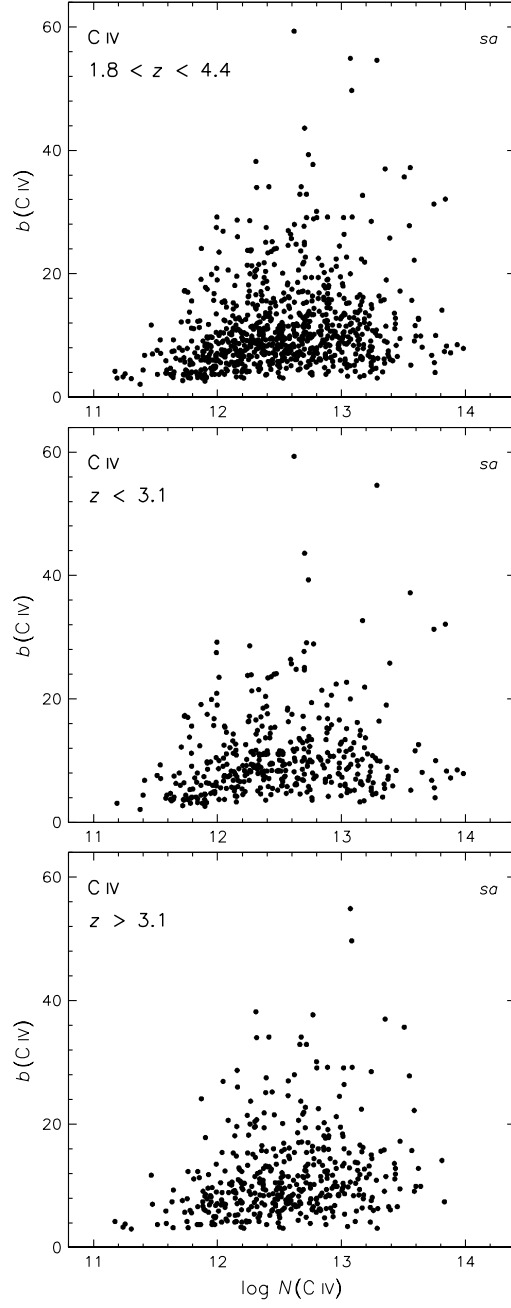


Fig. 10.— C IV Doppler parameter b (km s^{-1}) versus column density N (cm^{-2}) for all detected *components* of sample *sa*, also separately showing those with $z < 3.1$ and $z > 3.1$.

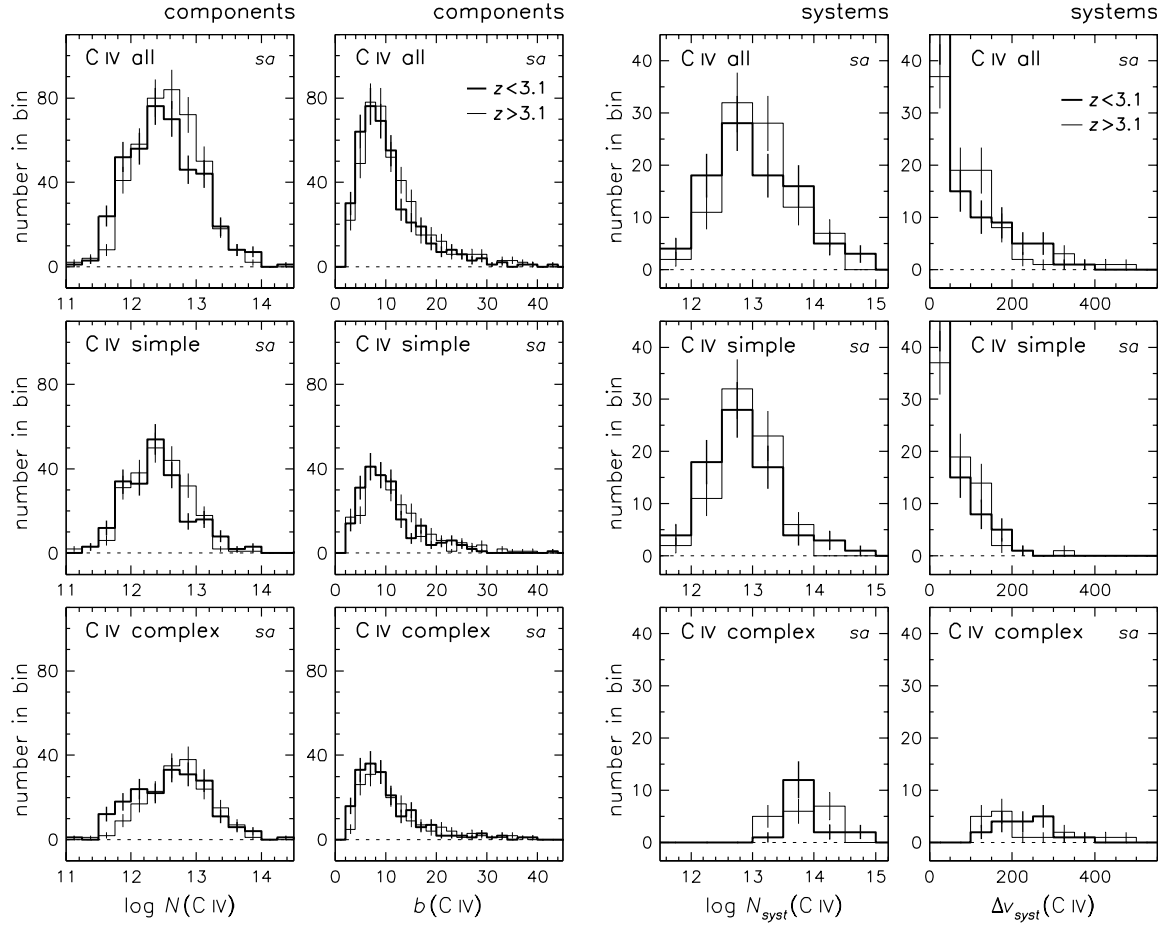


Fig. 11.— *Left panels:* Histograms of C IV column density N (cm^{-2}) and Doppler parameter b (km s^{-1}) for all detected *components* of sample *sa*, comparing values for $z < 3.1$ (*thick lines*) and $z > 3.1$ (*thin lines*) and showing the data for *all* systems, *simple* systems (≤ 6 identified components) and *complex* systems (≥ 7 identified components). *Right panels:* Histograms, imitating *left panels*, of *system* summed C IV column density N_{syst} (cm^{-2}) and velocity spread of the components within a system Δv_{syst} (km s^{-1}).

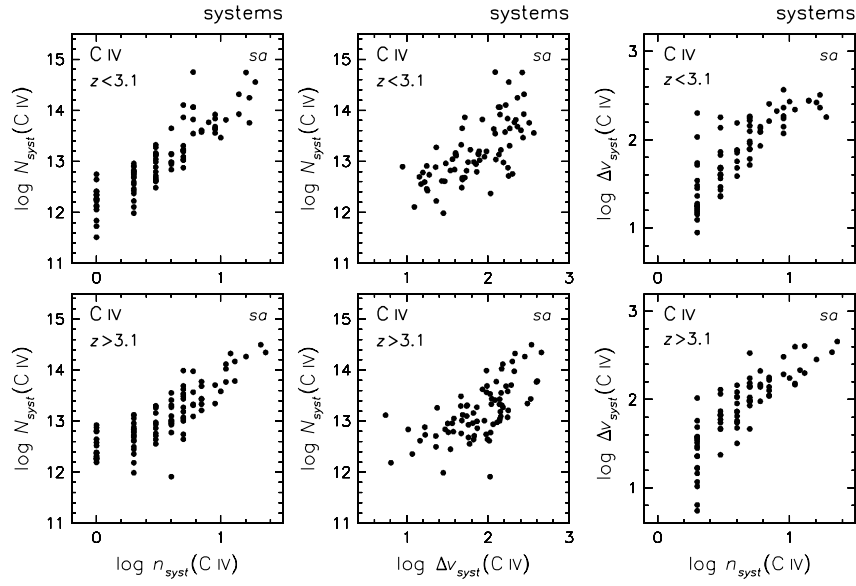


Fig. 12.— Relationships for all C IV *systems* of sample *sa* at redshifts $z < 3.1$ and $z > 3.1$, showing: *left panels*, system summed C IV column density N_{syst} (cm^{-2}) and number of components within a system n_{syst} ; *middle panels*, N_{syst} and velocity spread of system components Δv_{syst} (km s^{-1}); *right panels*, Δv_{syst} and n_{syst} .

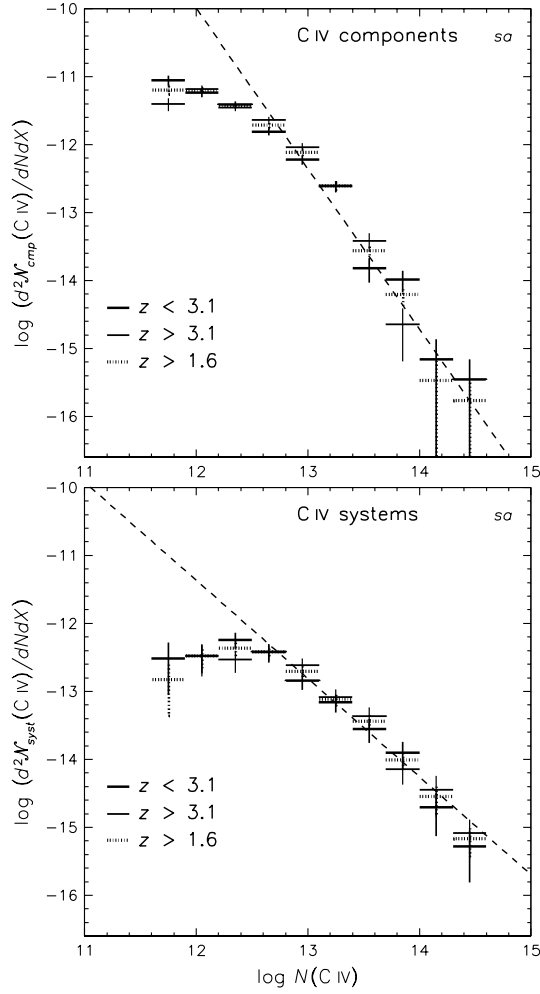


Fig. 13.— Differential column density distribution of C IV *components* (upper) and *systems* (lower) for sample *sa* covering redshifts $1.6 < z < 4.4$ and shown for ranges $z < 3.1$ (thick continuous lines), $z > 3.1$ (thin continuous lines) and the full extent $z > 1.6$ (dotted lines). The bin size (shown by horizontal bars) is $10^{0.3}N$ where N is the column density (cm^{-2}); errors (vertical bars) are $\pm 1\sigma$ values based on the number of absorbers N in each bin. The few densely-solid looking horizontal bars are manifestations of closely similar results from the different redshift selections. The dashed lines are power-law fits to the full data set as described in the text, with indices $\beta = 2.36 \pm 0.07$ (components) and $\beta = 1.68 \pm 0.09$ (systems).

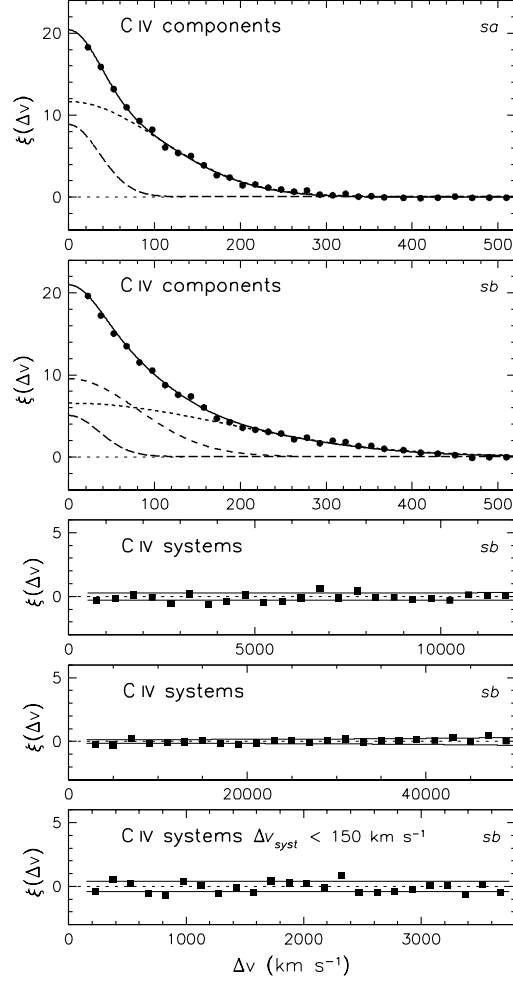


Fig. 14.— Two-point correlation functions $\xi(\Delta v)$ versus velocity separations Δv for C IV absorber redshifts spanning $1.6 \lesssim z \lesssim 4.4$ and separated by $\gtrsim 3000$ km s⁻¹ from the QSO nominal emission redshifts. *First panel:* Points give $\xi(\Delta v)$ for the individual *components* of sample *sa*, binned over 15 km s⁻¹ for $\Delta v \leq 370$ km s⁻¹ and 20 km s⁻¹ for $\Delta v \geq 370$; $\pm 1\sigma$ errors in the random distribution are smaller than the symbol size. A two-component Gaussian fit and the separate components of the fit are shown with parameters as given in the text. *Second panel:* Same as top panel, now including all components of the nine systems with significant Lyman α damping wings, using sample *sb*; a three-component Gaussian fit is shown. *Third panel:* Result for the *system* redshifts of sample *sb*, binned over 500 km s⁻¹ and extending to $\Delta v = 12000$ km s⁻¹; $\pm 1\sigma$ errors in the random distribution are shown by *bounding thin lines*. *Fourth panel:* Same as third panel but binned over 2000 km s⁻¹ and extending to $\Delta v = 50000$ km s⁻¹. *Fifth panel:* Same as third panel but using only systems having velocity spread $\Delta v_{\text{syst}} < 150$ km s⁻¹, binned over 150 km s⁻¹ and extending to $\Delta v = 3800$ km s⁻¹.

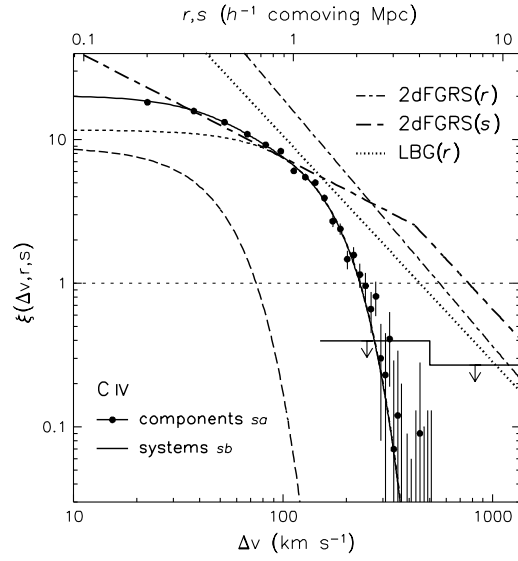


Fig. 15.— Comparison of C IV absorber and galaxy two-point correlation functions in logarithmic form. The C IV sample *sa* data for individual *components* are shown with the two-component Gaussian fit as in Figure 14; $\pm 1\sigma$ errors in the random distributions are given with the data points. Sample *sb* data for *systems* as described in the text are shown here as upper limits using $+1\sigma$ errors from Figure 14. Fits to results from the 2dF Galaxy Redshift Survey in real-space (*r*) and redshift-space (*s*) and in real-space for a sample of Lyman-break galaxies (LBG) use the upper axis, all as described in the text.

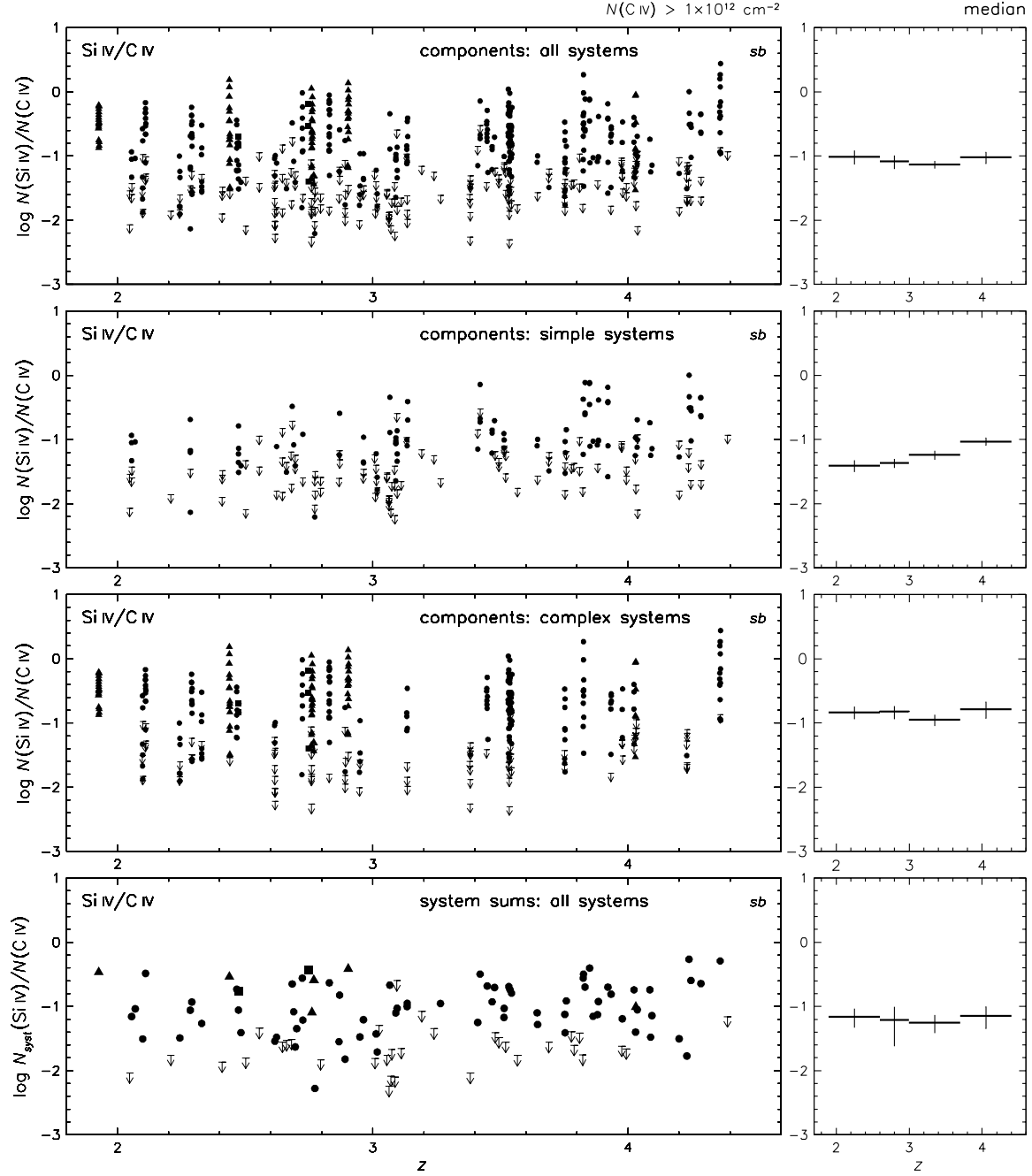


Fig. 16(a).— *Left panels:* Redshift evolution of Si IV/C IV column density ratios. Upper limits are 1σ values. The *upper three panels* show individual *component* values having $N(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$ from sample *sb* for *all systems*, *simple systems* (≤ 6 C IV components) and *complex systems* (≥ 7 C IV components). *Circles* show values obtained outside the Lyman forest; reliable values from lines in the forest are identified by *squares*; selected components clear of regions of high $N(\text{H I})$ in systems containing significant Lyman α damping wings are shown by *triangles*, and by *diamonds* if also in the forest. The *bottom panel* gives values obtained from *summed* column densities for all available *systems* in sample *sb* having $N_{\text{sys}}(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$. *Right panels:* Redshift evolution of corresponding median values, obtained over the extent of each horizontal bar, indicated with 1σ error bars (see text).

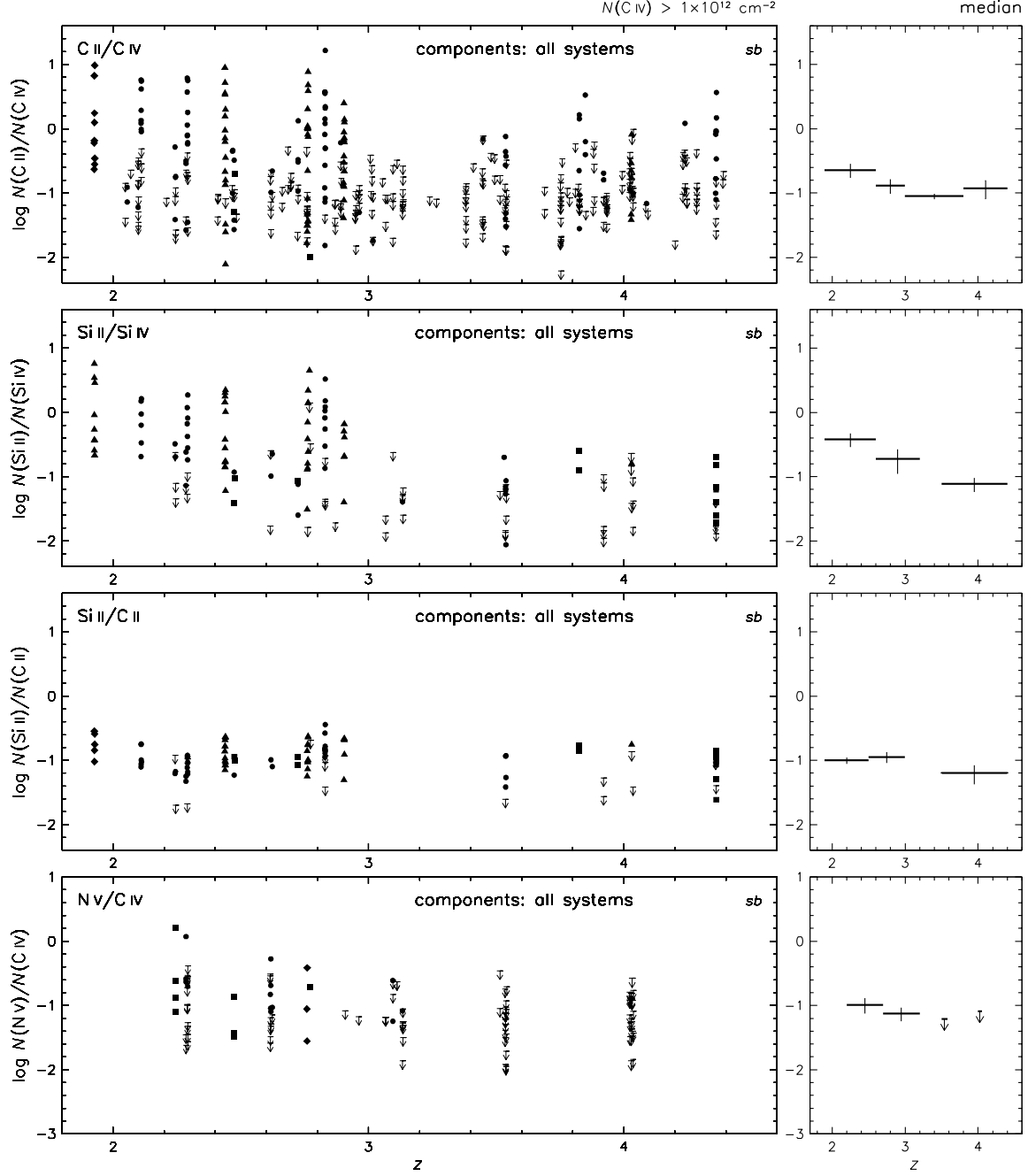


Fig. 16(b).— Same as for the *top* panels in Figure 16(a), here for the *component* column density ratios: C II/C IV, Si II/Si IV (having *detected* Si IV with $N(\text{Si IV}) > 5 \times 10^{10} \text{ cm}^{-2}$); Si II/C II (having *detected* C II with $N(\text{C II}) > 5 \times 10^{11} \text{ cm}^{-2}$); N V/C IV. All cases arise from components having $N(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$.

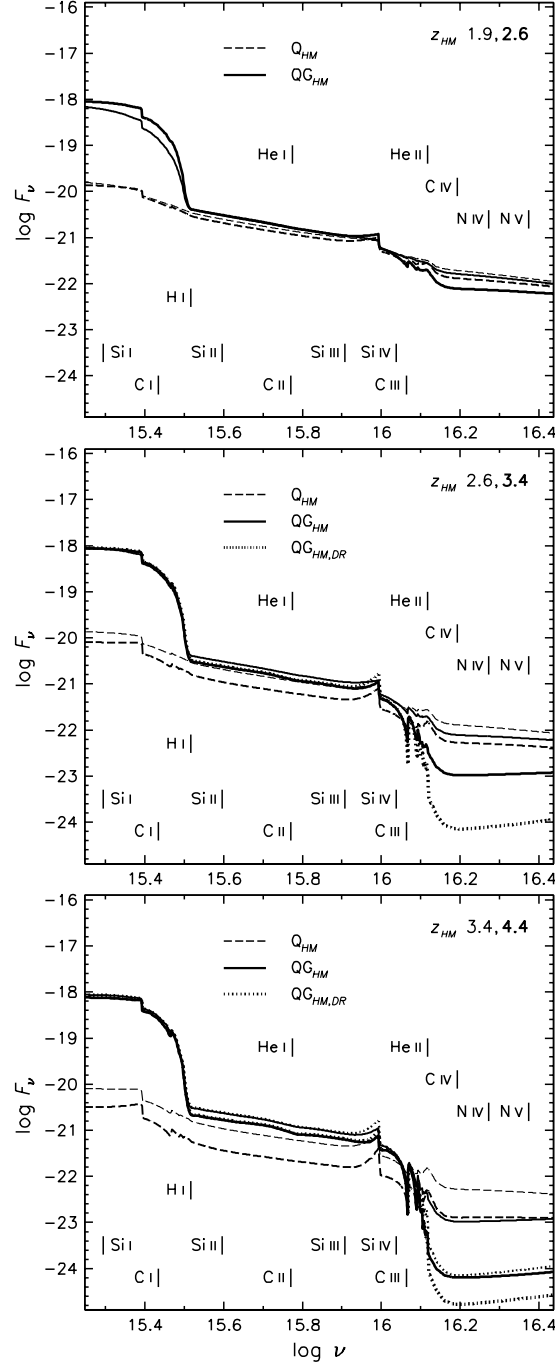


Fig. 17(a).— Spectral energy distributions of the metagalactic ionizing radiation background (Haardt & Madau 2012) plotted as flux F_ν , $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$ (see text) against frequency ν Hz in the range effective for photoionization of the species studied in this paper (relevant ionization thresholds are shown), at bounding redshifts z_{HM} of the intervals selected for the ionic displays in Figure 17(b). Three spectral cases are included (see text): (i) partial model using QSO sources alone (Q_{HM}), in *dashed lines*; (ii) full model with QSOs and star-forming galaxies ($Q_{G_{HM}}$), in *continuous lines*; (iii) model simulating delayed reionization of He II (see text) at $z_{HM} = 3.4$ and 4.4 ($Q_{G_{HM},DR}$), in *dotted lines*. Note the *thin-thick* coded in correspondence with the indicated z_{HM} boundaries.

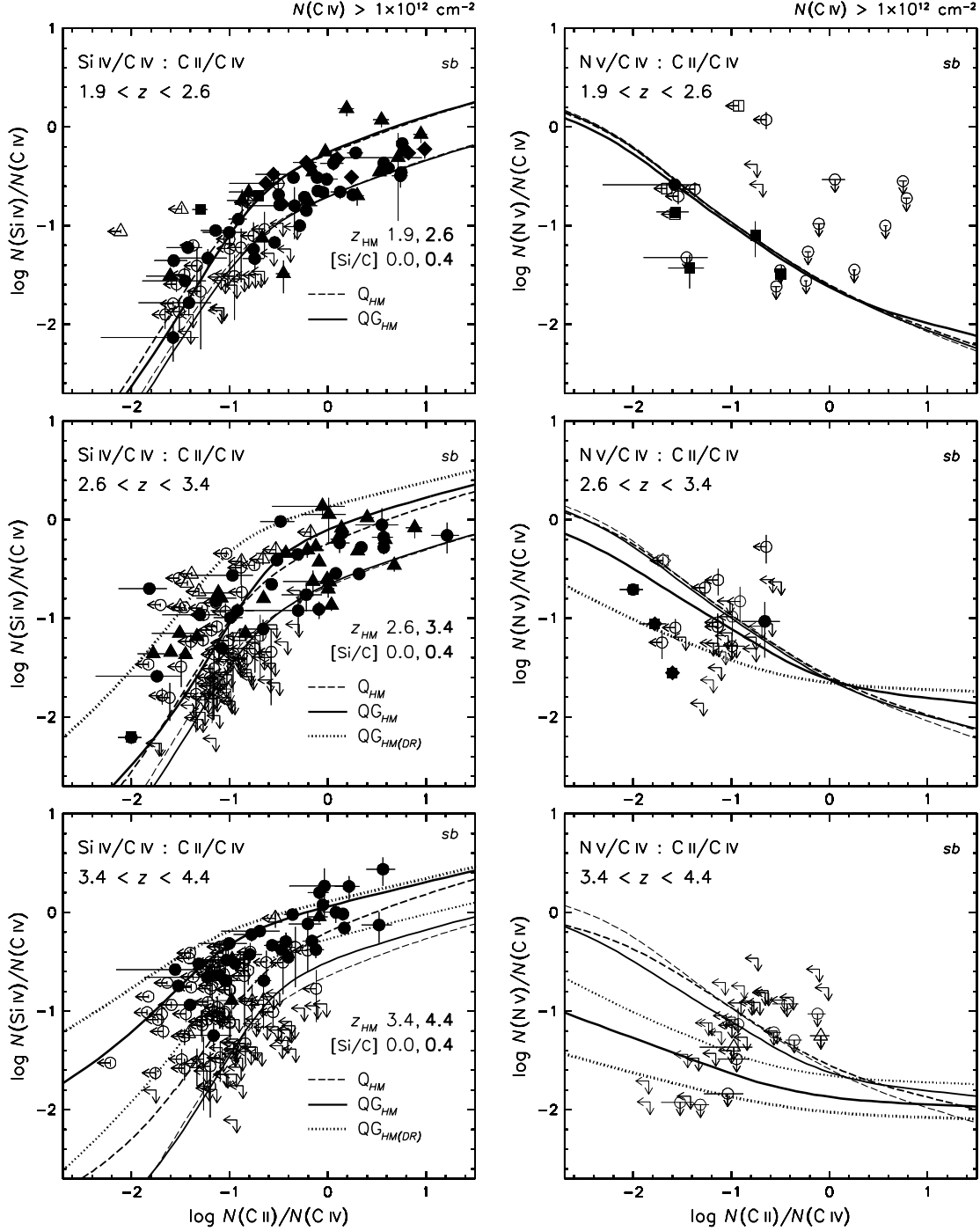


Fig. 17(b).— Two-dimensional column density ratios $\text{Si IV/C IV} : \text{C II/C IV}$, $\text{N V/C IV} : \text{C II/C IV}$, $\text{Si II/Si IV} : \text{C II/C IV}$ and $\text{Si II/C II} : \text{C II/C IV}$ for all *components* in sample *sb* having $N(\text{C IV}) > 1 \times 10^{12} \text{ cm}^{-2}$. Data symbols are defined in Figure 16(a). Error bars give $\pm 1\sigma$ uncertainties. Upper limit arrows point from $+1\sigma$ values; cases where one of the two ionic ratios is an upper limit have an *open* symbol. The curves are model predictions of the CLOUDY code at the bounding redshifts z_{HM} for the spectral models in Figure 17(a) (see text) with fiducial absorbers (see text) and $[\text{Si/C}] = 0.0, 0.4$ (see text) applied respectively at the lower and upper redshift for each pair containing Si IV/C IV or Si II/C II . Similarly, N V/C IV has $[\text{N/C}] = 0.0, -1.4$ (see text) but is shown only for the solar case; the progression down to $[\text{N/C}] = -1.4$ remains implied here and in all similar following figures. All curves are *thin-thick* redshift coded in correspondence with the z_{HM} boundaries.

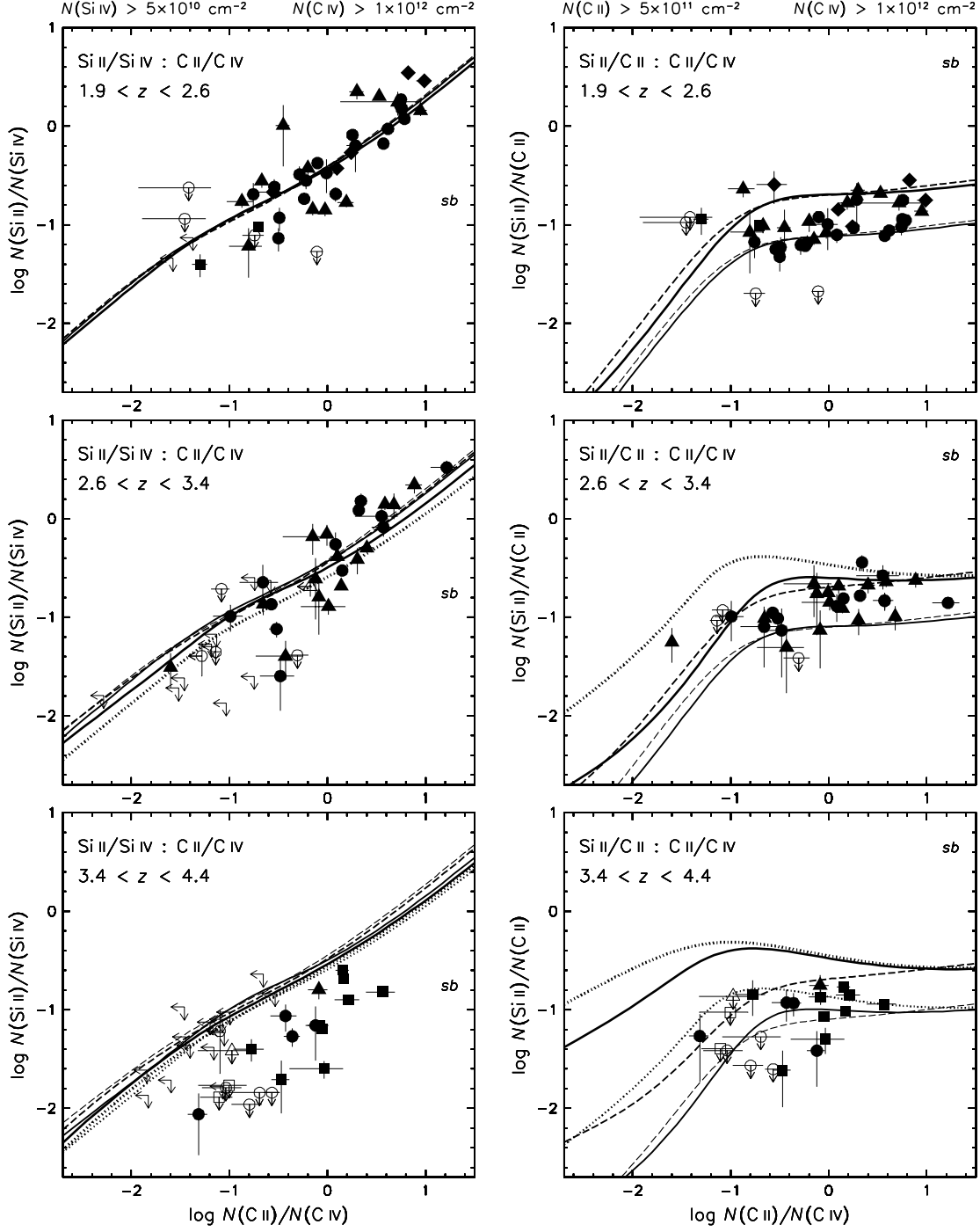


Fig. 17(b).— Continued. Note the additional imposed requirements of *detected* $N(\text{Si IV}) > 5 \times 10^{10} \text{ cm}^{-2}$ and $N(\text{C II}) > 5 \times 10^{11} \text{ cm}^{-2}$ as respective bases for Si II/Si IV and Si II/C II.

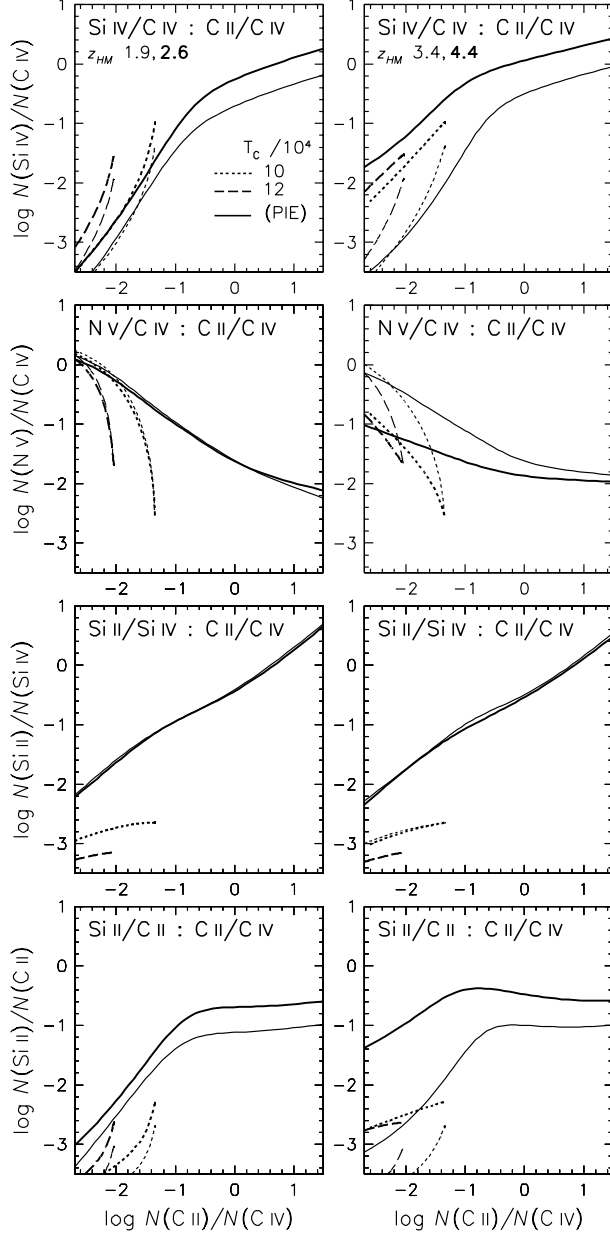


Fig. 18.— CLOUDY models for $\text{Si IV/C IV} : \text{C II/C IV}$, $\text{N V/C IV} : \text{C II/C IV}$, $\text{Si II/Si IV} : \text{C II/C IV}$ and $\text{Si II/C II} : \text{C II/C IV}$ at the bounding redshifts $z_{HM} = 1.9, 2.6$ and $3.4, 4.4$, following the style of the displays in the corresponding panels of Figure 17(b) but with downward extended axes. The coded *dashed lines* show results for collisional ionization equilibrium models at the two fixed temperatures near 10^5 K as indicated, in the presence of the Haardt & Madau (2012) Q_{GHM} metagalactic ionizing radiation background and the cosmic microwave background (see text) and using the fiducial absorber properties including both values of $[\text{Si/C}]$ as in Figure 17(b); the curves terminate within each diagram where the process becomes independent of density. For comparison the corresponding models in pure photoionization equilibrium (PIE) from Figure 17(b) are included separately in *continuous lines*. For each case note the respective *thin-thick* redshift coding of the model curves.

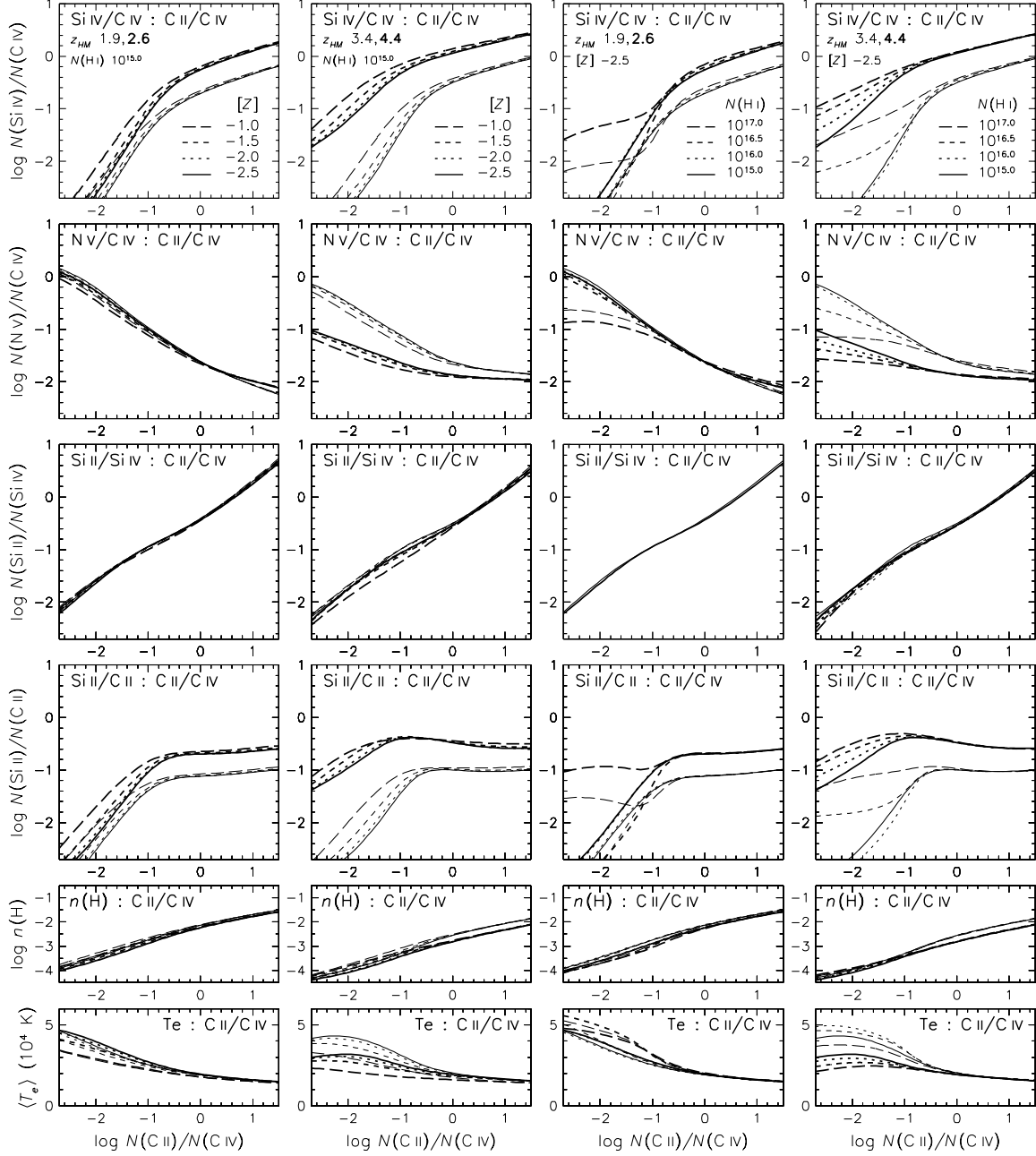


Fig. 19.— CLOUDY models in photoionization equilibrium using the Haardt & Madau (2012) $Q\dot{G}_{HM}$ metagalactic ionizing radiation background and the cosmic microwave background (see text) for the bounding redshifts $z_{HM} = 1.9, 2.6$ and $3.4, 4.4$, following the corresponding displays in Figure 17(b) including both values of $[\text{Si}/\text{C}]$, but here with absorber parameters arbitrarily differing in metallicity, $[Z]$, and neutral hydrogen column density, $N(\text{H I}) \text{ cm}^{-2}$, in coded *dashed lines* as indicated; the fiducial case with $[Z] = -2.5$ and $N(\text{H I}) = 10^{15.0} \text{ cm}^{-2}$ used in Figure 17(b) is shown in all panels by *continuous lines*. The apparent trends are discussed in the text. In the *bottom two sets of panels* are related displays for total hydrogen volume density, $n(\text{H})$, this indicating broad proportionality with $\text{C II}/\text{C IV}$, and mean temperature within the absorber gaseous column, $\langle T_e \rangle$. For each case note the respective *thin-thick* redshift coding of the model curves.

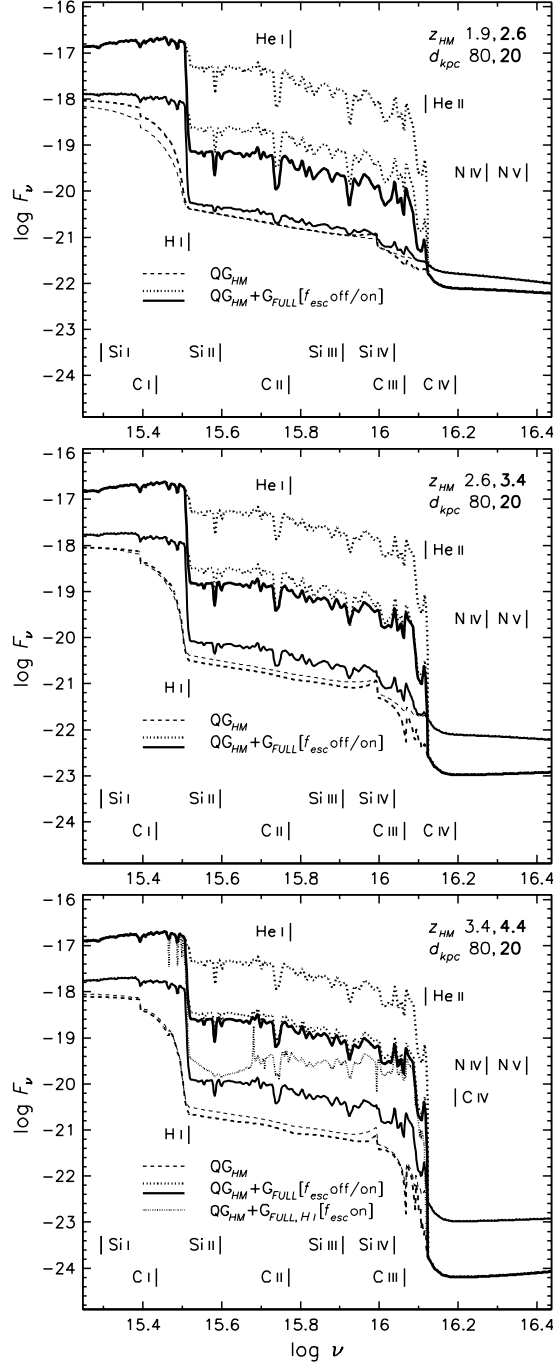


Fig. 20(a).— Spectral energy distributions plotted as in Figure 17(a), here for the Haardt & Madau (2012) QG_{HM} background augmented by radiative contributions from local template galaxies at 80 and 20 physical kpc from the absorbers ($QG_{HM}+G_{FULL}$) (see text), in *continuous lines*. For reference, corresponding cases having the galactic spectra without applied escape fraction are shown in *thick dotted lines*, and the basic QG_{HM} background from Figure 17(a), in *dashed lines*. All are *thin-thick* redshift-coded in correspondence with the z_{HM} boundaries. Included in the *bottom panel* at $z_{HM} = 4.4$ is a spectrum with the local galaxy contribution G_{FULL} attenuated by intrinsic H I having $N(\text{H I}) = 10^{18} \text{ cm}^{-2}$ ($QG_{HM}+G_{FULL, HI}$), in *fine dotted line*.

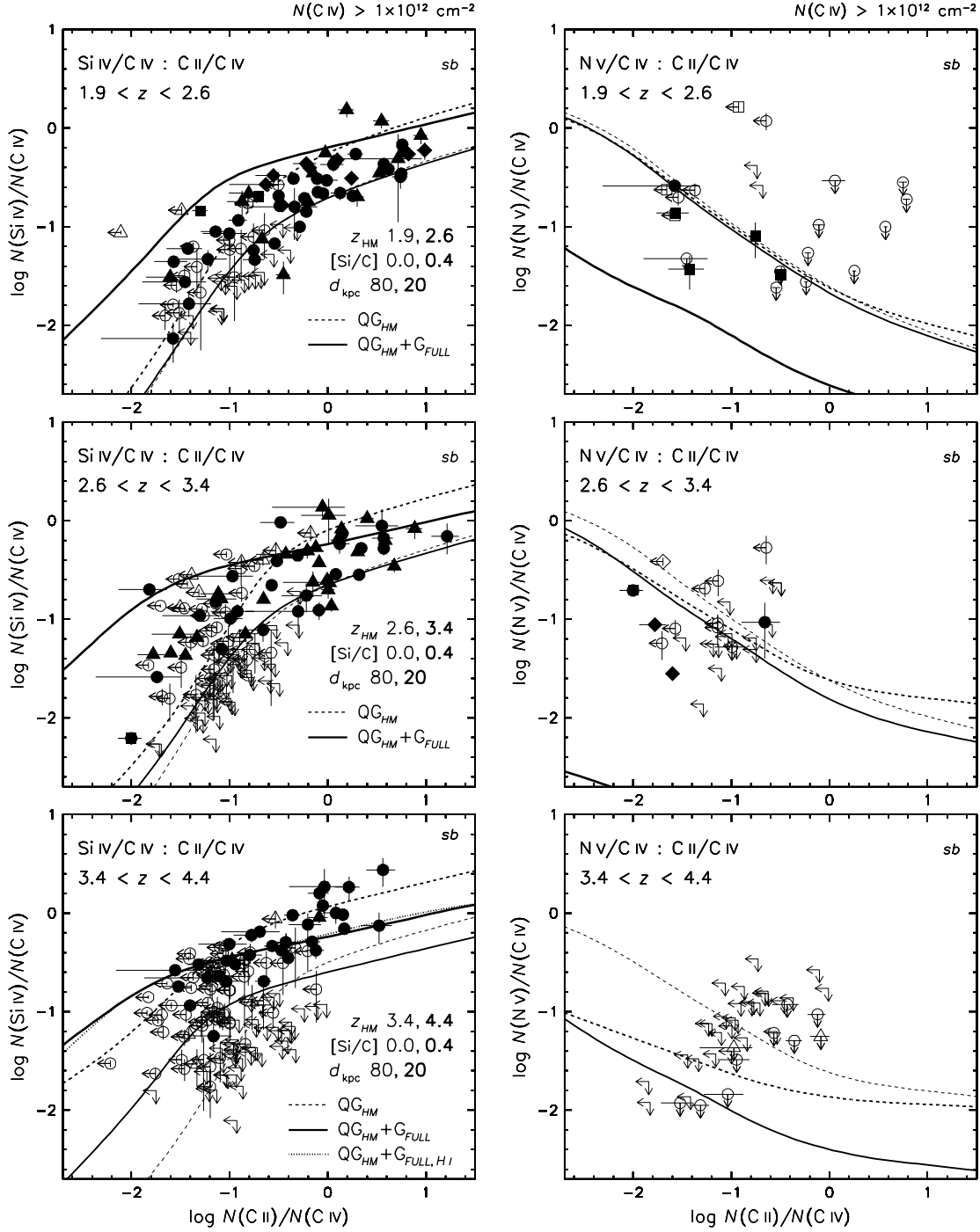


Fig. 20(b).— CLOUDY models of two-dimensional column density ratios at the bounding redshifts z_{HM} for the radiative cases in Figure 20(a) and similarly coded, with fiducial absorbers (see text), and associated data points, all plotted as in Figure 17(b) and described in its caption. The basic Haardt & Madau (2012) QG_{HM} background from Figure 17(b) is shown in *thin dashed lines*. All in the figure except the single case $QG_{HM} + G_{FULL, HI}$ are *thin-thick* redshift-coded in correspondence with the z_{HM} boundaries.

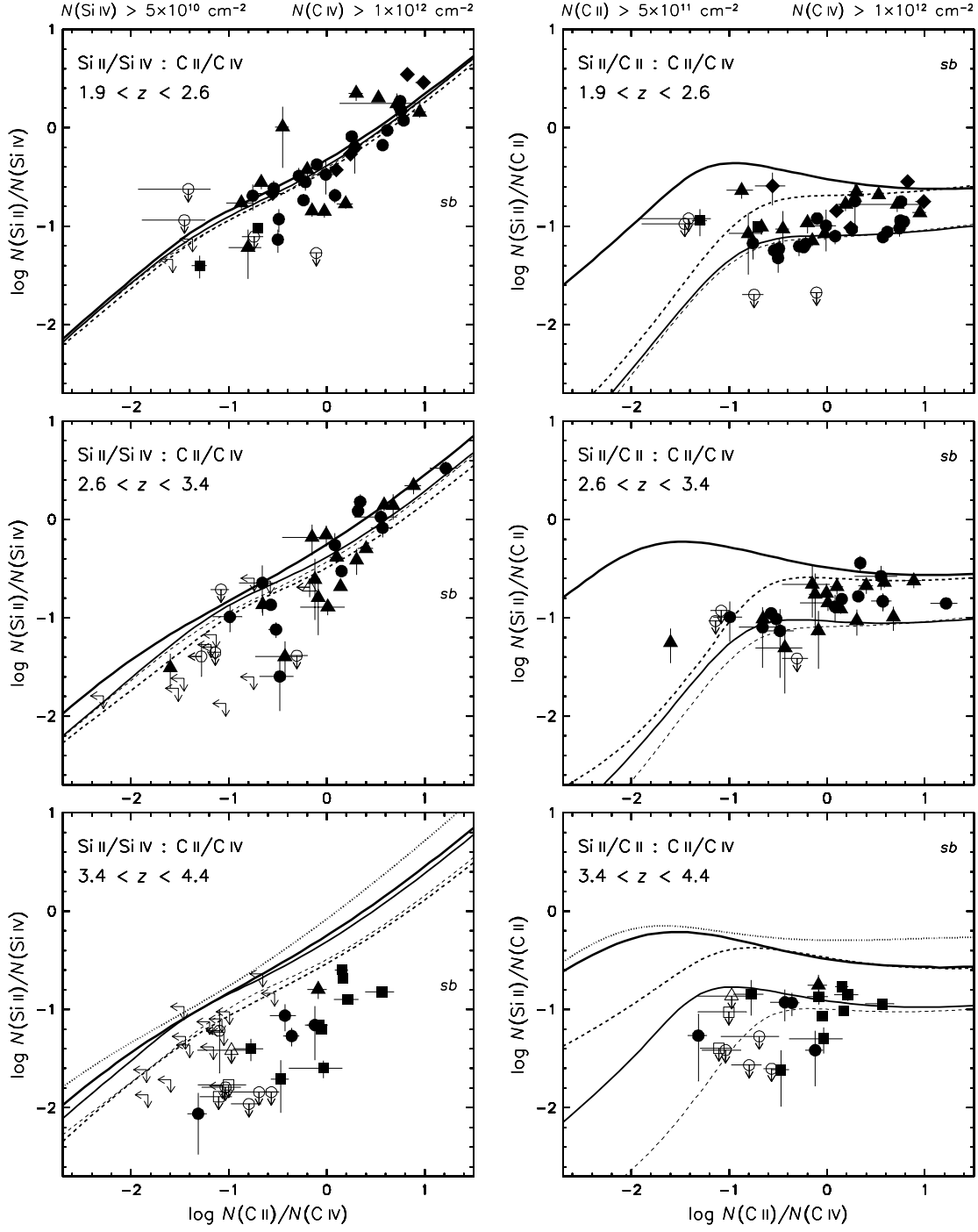


Fig. 20(b).— Continued. Note the caption to the equivalent part of Figure 17(b).

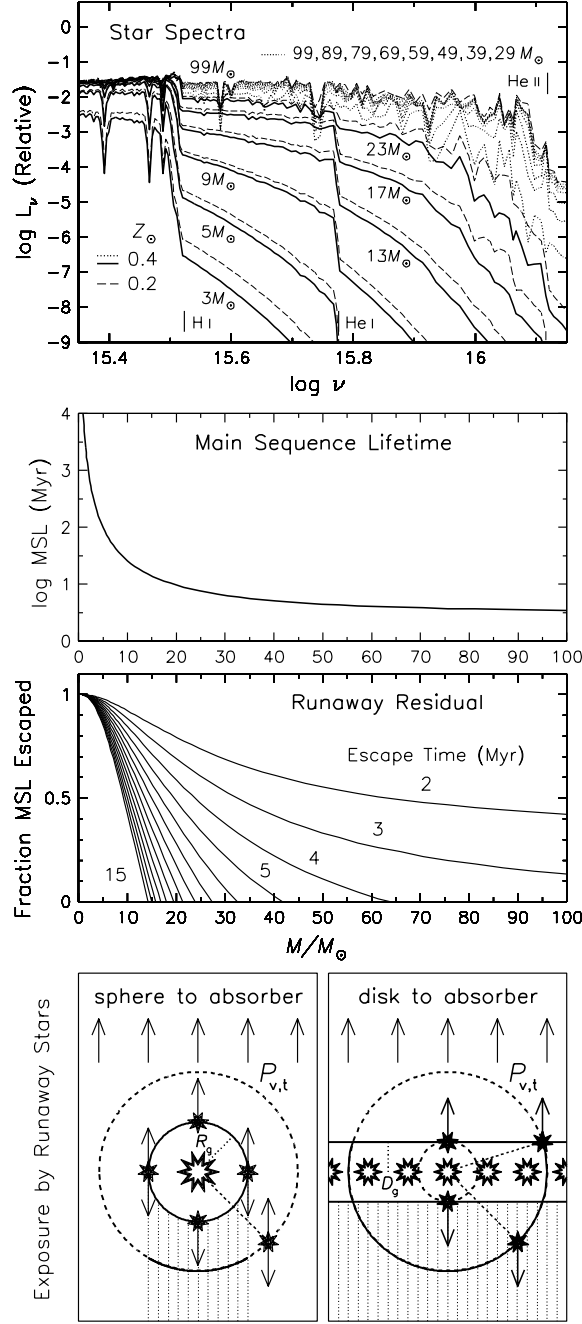


Fig. 21.— *First panel:* Intrinsic spectra of component stellar $2 M_\odot$ slices selected from the sets of metallicity 0.2 and 0.4 Z_\odot obtained using Starburst99 as described in the text, here highlighting the region containing the H I, He I and He II ionization thresholds (marked). The pairs of components labeled 99 and over 3–23 M_\odot indicate the relatively small spectral differences between the two metallicities (the rest shown here are of the higher metallicity only). *Second panel:* Stellar main sequence lifetime (MSL) shown against mass (M/M_\odot) for metallicity 0.3 Z_\odot , from Hurley et al. (2000). *Third panel:* For runaway stars over the mass range and a set of trial *potential* intervals for escape from obscuration of ionizing radiation, showing the fraction of MSL remaining after reaching the effective boundary of the galaxy. *Fourth panel:* Depictions of a central section through a spheroidal galaxy and a central vertical section through a disk-like galaxy, indicating compact star-forming regions. Absorptive boundaries are shown respectively by a *continuous circle* and *continuous horizontal lines*. Scenarios for illumination of a relatively distant absorber by runaway stars are described in the text. Circles of *partially dashed and continuous lines* indicate positions of stars at a time after ejection at a given velocity (see text). Arrows indicate specific directions of radiation.

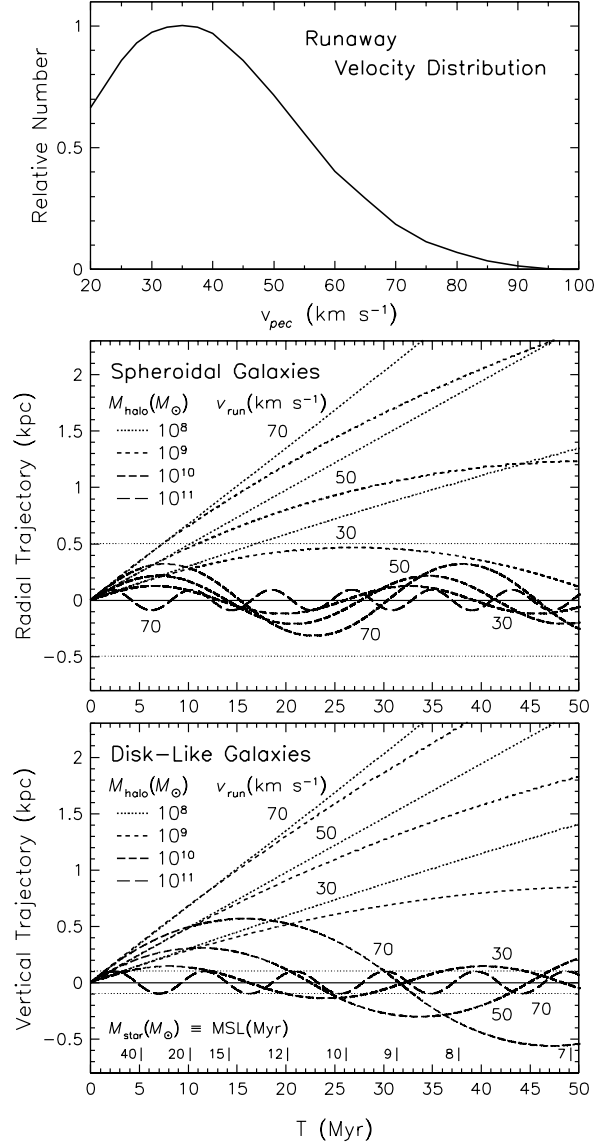


Fig. 22.— *Top panel:* Runaway star velocity distribution from Tetzlaff et al. (2011), common to all stellar masses. *Middle panel:* Temporal displays of a selection of typical *radial* trajectories of runaway stars with indicated velocities v_{run} initiated at the centre of model *spheroidal* galaxies having spheroidal dark matter halos of indicated mass and baryonic content 0.17 of halo mass (see text for details). The *dotted horizontal lines* indicate the baryonic radial softening length applied in the example shown here. *Bottom panel:* Similar presentation for a selection of *vertical* trajectories initiated at the central plane of model *disk-like* galaxies having spheroidal dark matter halos (see text for details). Notice in both that stars with trajectories that return to the galaxy pass through and out again on the other side. Marked along the bottom time axis but applicable to both displays are indicative positions of main sequence lifetimes of stars of shown mass in the active range of significance here (refer also to the *top panel* of Figure 21).

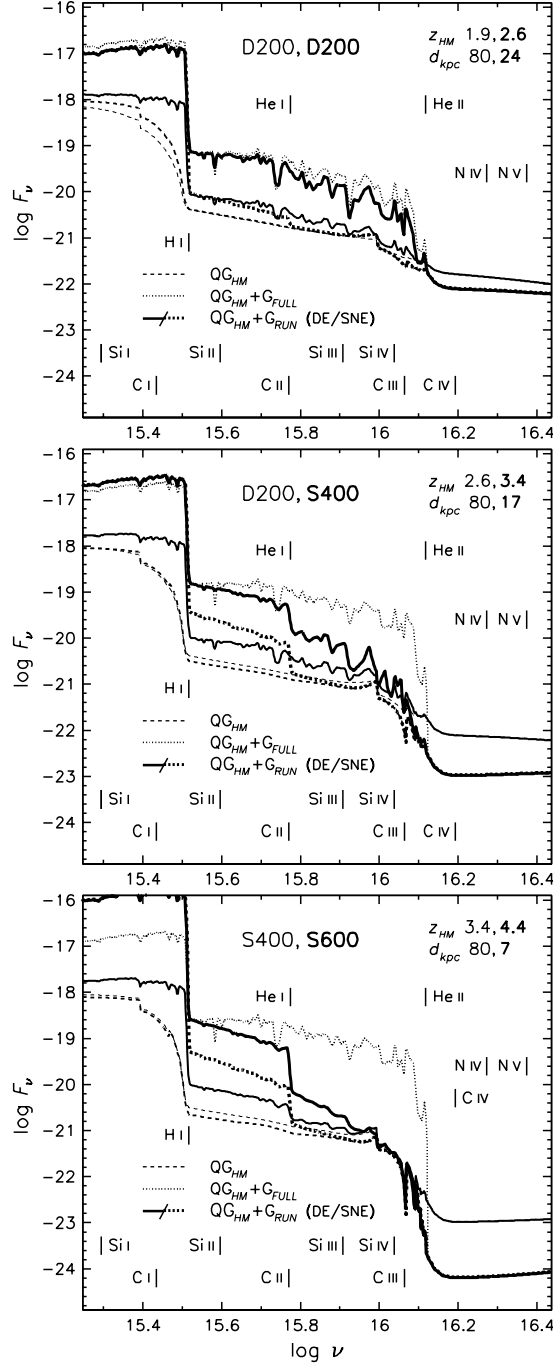


Fig. 23(a).— Spectral energy distributions plotted as in Figure 17(a), here for the Haardt & Madau (2012) QG_{HM} background augmented by radiative contributions from local template galaxies due to runaway stars (identified G_{RUN}) over ranges of internal escape intervals to the gaseous boundaries of the galaxies as labeled (e.g.: D200, indicating a disk-like galaxy with escape height 200 pc; S400, a spheroidal galaxy with escape radius 400 pc) (see text) and positioned at indicated physical kpc from the absorbers. Included are *dynamically ejected stars* (DE), in *continuous lines*, and *supernova ejected stars* (SNE), in *bold dotted lines* (shown only at the higher redshift in each panel). For comparison, $QG_{HM}+G_{FULL}$ from Figure 20 are included at the higher redshift in each panel, in *fine dotted lines*. The basic QG_{HM} background from Figure 17(a) is in *dashed lines*. *Thin-thick* redshift coding in correspondence with the z_{HM} boundaries is applied where necessary.

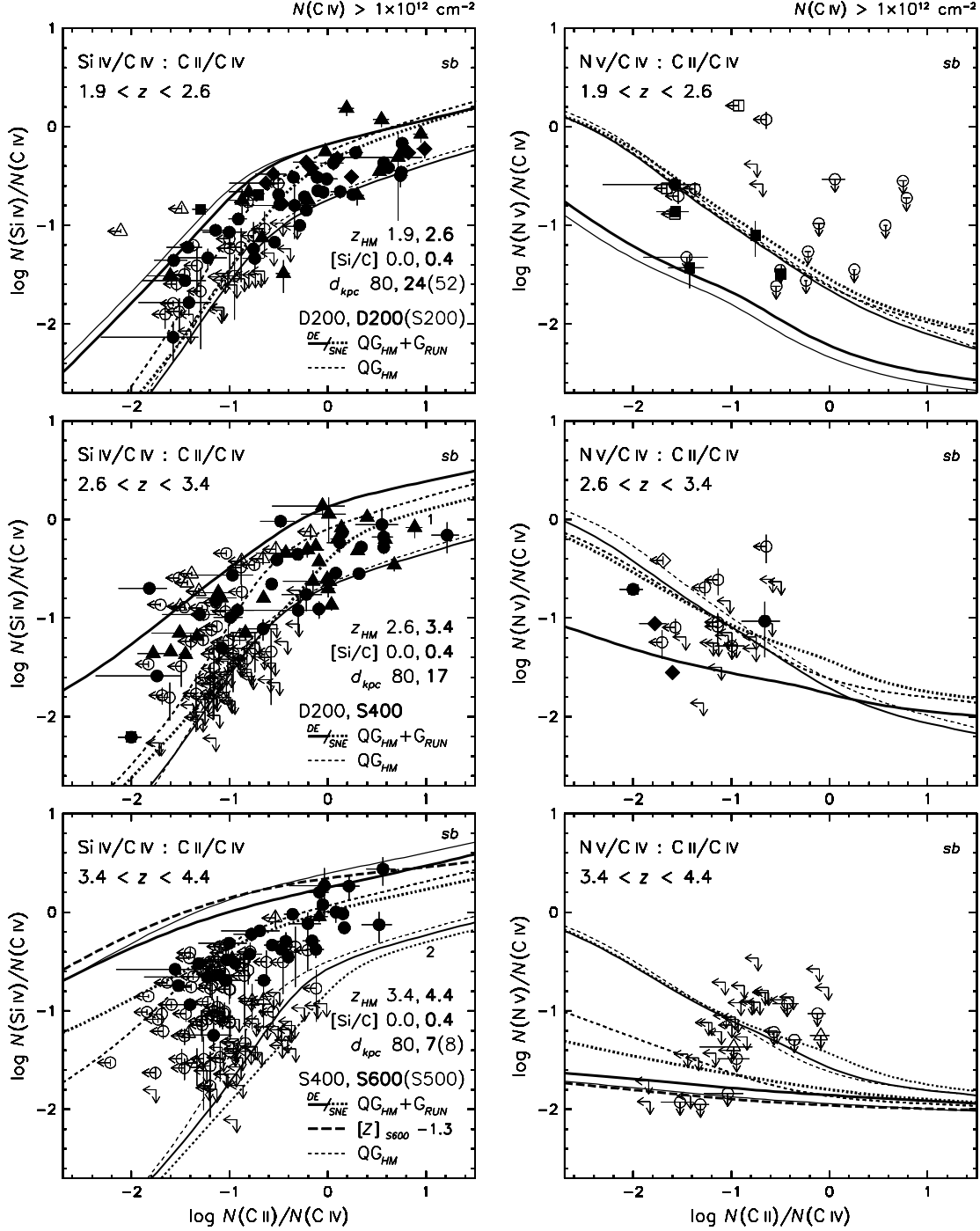


Fig. 23(b).— CLOUDY models of two-dimensional column density ratios at the bounding redshifts z_{HM} for the radiative cases in Figure 23(a) and similarly coded, with fiducial absorbers (see text), and associated data points, all plotted as in Figure 17(b) and described in its caption. In addition, in the *top panels* there is a case at $z_{\text{HM}} = 2.6$ for a spheroidal model S200 and in the *bottom panels* a case at $z_{\text{HM}} = 4.4$ for S500, both in *thin continuous lines*; also in the *bottom panels* the SNE runaway case from the *middle panels* at $z_{\text{HM}} = 3.4$ (indicated 1) is now displayed for the lower boundary $[\text{Si/C}] = 0.0$ (indicated 2); and at $z_{\text{HM}} = 4.4$ is a case for S600 with the metallicity $[\text{Z}]$ of the absorber raised from the fiducial value (-2.5) to -1.3 , in *thick dashed lines*; see text for all these cases. The basic QG_{HM} background from Figure 17(b) is in *thin dashed lines*. *Thin-thick* redshift coding in correspondence with the z_{HM} boundaries is applied where necessary.

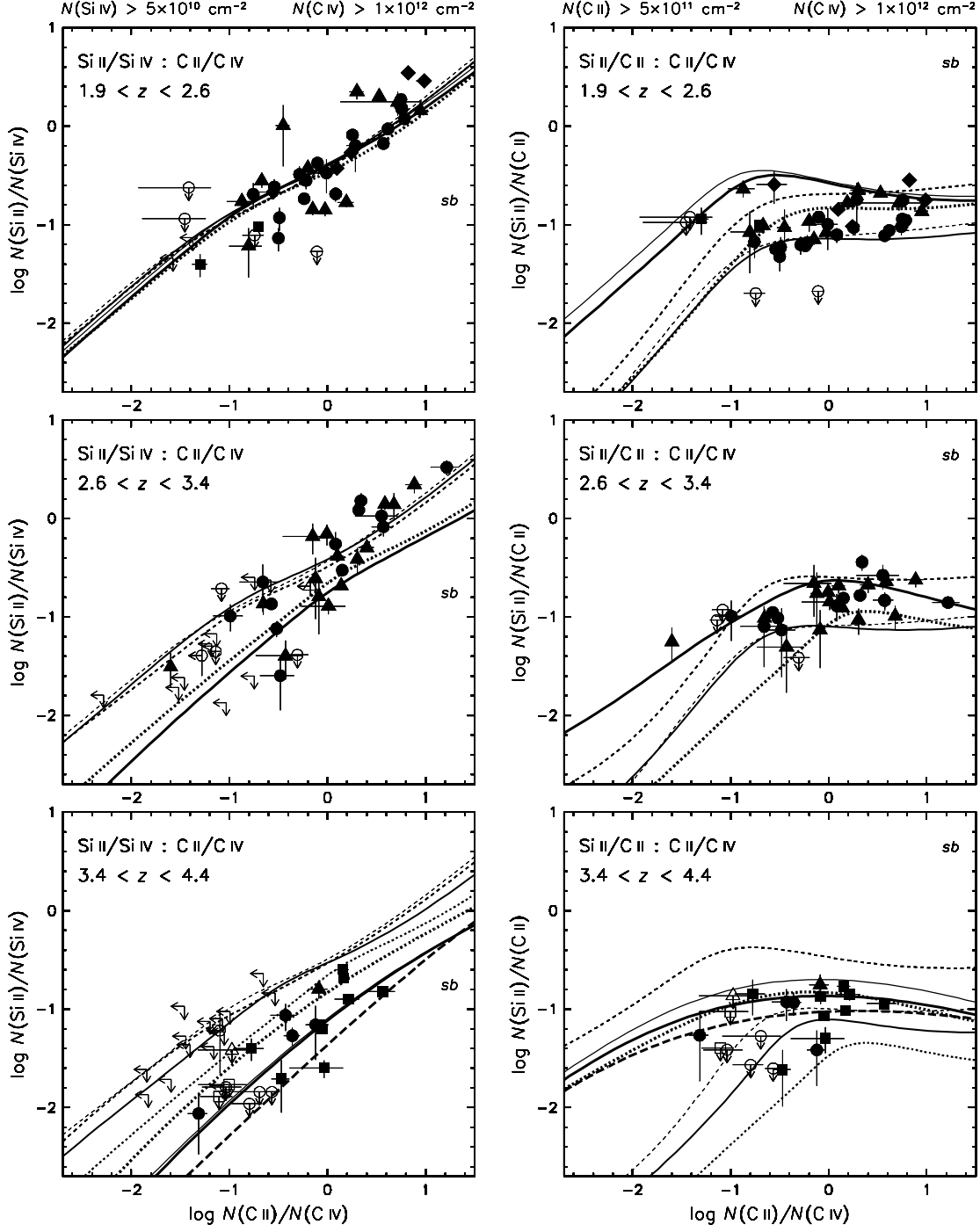


Fig. 23(b).— Continued. Note the caption to the equivalent part of Figure 17(b).

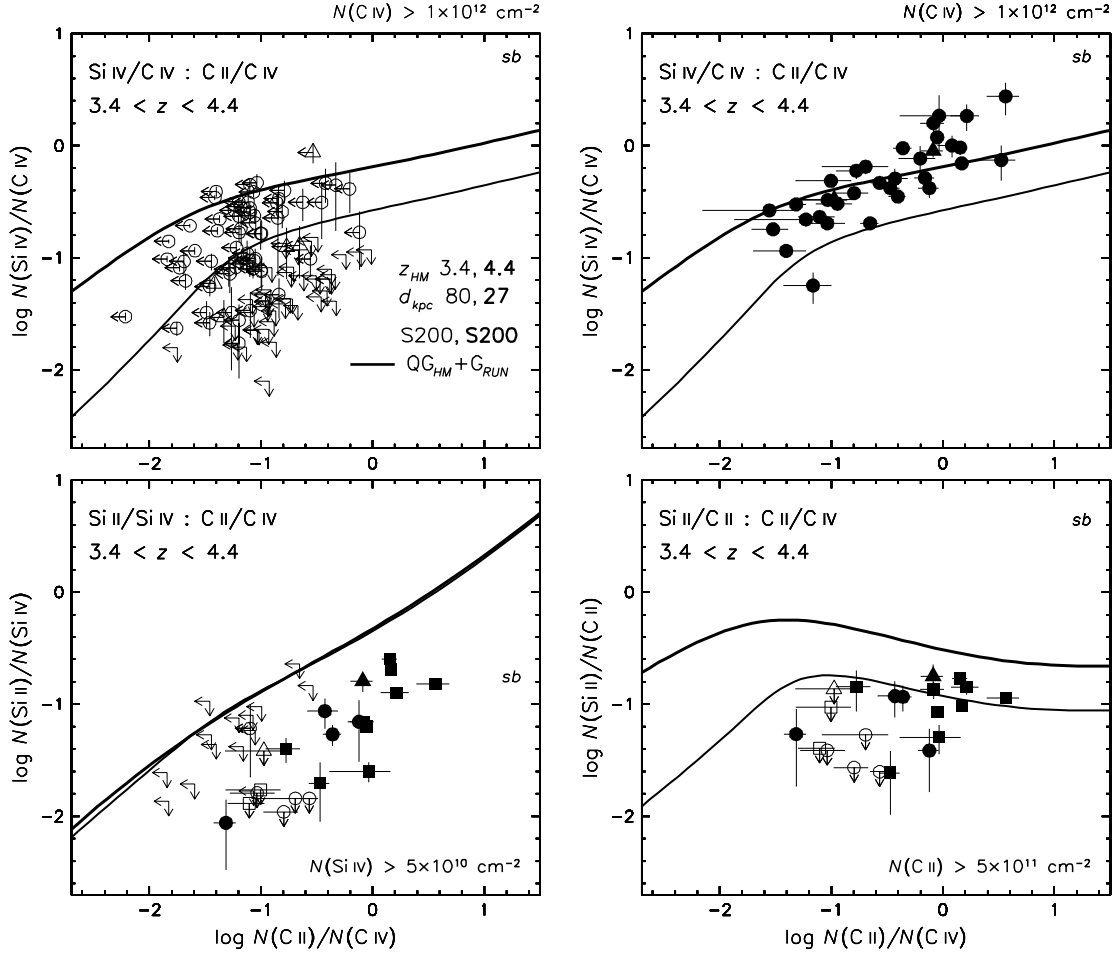


Fig. 24.— CLOUDY model predictions of two-dimensional column density ratios for the fiducial absorbers exposed to metagalactic ionizing radiation at the bounding redshifts $z_{HM} = 3.4, 4.4$ and local radiation received at the indicated distances from *dynamically ejected* runaway stars (DE) escaping a spheroidal galactic structure S200, described in the text; the cosmic microwave background at these redshifts is included. The model curves are *thin-thick* redshift-coded as indicated. The *upper left panel* contains all Si IV/C IV : C II/C IV upper limit cases from the corresponding panel in Figure 23(b); the associated full detections are shown in the *upper right panel*. In the *lower panels* are the Figure 23(b) counterpart cases for Si II/Si IV : C II/C IV and Si II/C II : C II/C IV, here integrally including the upper limits (however, as explained in Figure 17(b), in particular for the latter only Si II upper limits can be present because *detected* C II is needed as the base for the ratio Si II/C II). Refer also to Figure 23(b) for N V/C IV : C II/C IV relating to the above and all panels for $1.9 < z < 2.6$ and $2.6 < z < 3.4$: the balance between full detections and indications from upper limits highlighted here for $3.4 < z < 4.4$ develop progressively over the whole observed redshift range.